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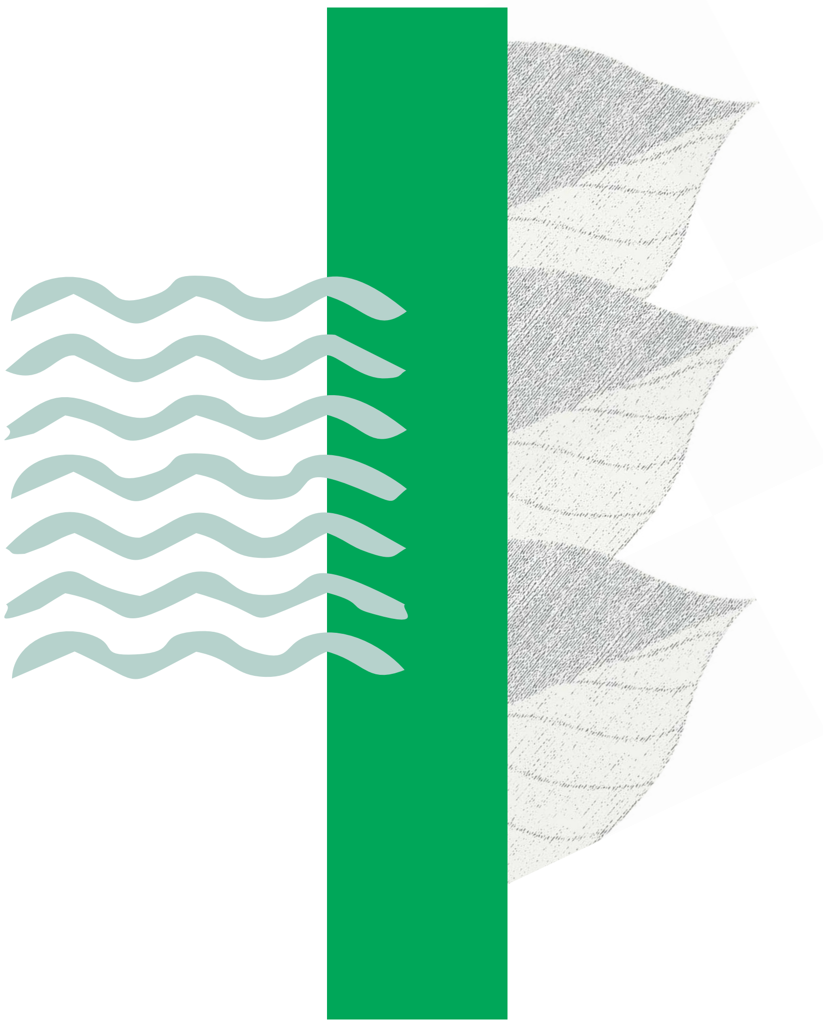

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HUMAN-AI COLLABORATION IN SCIENCE EDUCATION: CHALLENGES AND STEPS FORWARD

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AI technologies are reshaping our world and prompting education scholars to rethink both the aims and methods of schooling to prepare learners for the future (Holmes et al., 2019). Meanwhile, interest in integrating AI into science education has grown, with much discussion focusing on the impact of AI on student engagement and learning performance. Among those interests and debates, questions arise about AI's ability to provide instructional, learning, and evaluative tools, as well as the practices and challenges of teacher-AI collaboration in education.

A consistent finding across recent studies is that AI can augment, not replace, teacher expertise. When AI is thoughtfully designed and supported, AI-enabled environments support multimodal, collaborative learning that combines teacher guidance with learner autonomy. Across the literature, several roles for AI for different stages of science teaching emerged, including co-planning and co-teaching (e.g., Nazaretsky et al., 2022; Williyan et al., 2024; Yorulmaz et al., 2025), co-creating content and resources, promoting project-based learning and game-based learning pedagogies (Lee et al., 2021), and co-assessing of the learning process (Nazaretsky et al., 2022), to name a few. Along with all those roles, AI is capable of providing more targeted feedback and boosting students' engagement (Erduran, 2023).

While these findings indicate that AI can scaffold inquiry, surface alternative explanations, and diversify instructional strategies while preserving teacher decision-making authority, challenges exist in human-AI collaboration in education. One thing worth mentioning is that the combination of human intelligence and artificial intelligence is not always more effective than doing it by human or AI alone, since human-AI collaboration operates along a dynamic spectrum, requiring different balances of human control and AI automation depending on the nature of the learning task, learning environment, and the individuals' competency. However, currently, we still lack empirical evidence of best practices regarding the patterns and effectiveness of human-AI collaboration in education, especially in science education. A recent meta-analysis on the effectiveness of human-AI collaboration (in general) found that human–AI combinations performed differently based on types of task and the ability of both human and AI (Vaccaro et al., 2024). Evidence from HAIC in education suggests that AI systems frequently underperform relative to humans in several key areas: reading students' emotions during learning, interpreting social interactions, and grasping domain-specific knowledge that is not adequately captured by training data (Cohn et al., 2025). Consequently, hybrid approaches that combine human expertise with AI are needed to address these limitations. We need more empirical studies like this that address these questions and contribute to our understanding of the best human-AI collaboration trajectories and the outcomes that different trajectories lead to.

Looking forward, what concrete steps should researchers, educators, and policymakers take to advance responsible, effective human–AI collaboration in science education? To begin, promote professional development that enables teachers to participate in co-design and iterative refinement of AI-enhanced curricula. This includes promoting trust in AI technology among teachers since it is essential for successfully integrating AI into organiza-

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tions (Glikson & Woolley, 2020), training on interpreting AI outputs, contextualizing AI recommendations within disciplinary goals, and maintaining a critical stance toward AI recommendations. Second, cultivate open, adaptable AI tools co-created with teachers to ensure relevance to diverse classrooms and contexts (Williyan et al., 2024). Third, research and implement robust assessment frameworks that capture not only student achievement, shifts in scientific reasoning, collaboration, and AI literacy, but also dynamic changes in the human-AI collaboration loops. Finally, align AI integration with disciplinary standards and inquiry-based pedagogy, ensuring that AI augments, rather than fragments, the coherence of science learning.

To conclude, human–AI collaboration in science education offers substantial potential to enrich teaching and learning, on the condition that AI functions as a collaborative partner guided by teacher expertise, ethical principles, and a commitment to equity. Realizing this potential requires deliberate, evidence-based design decisions, professional development that centers on teacher agency, and governance frameworks that foster trust and transparency in AI-assisted learning. By sustaining an ongoing partnership among teachers, researchers, and AI developers, we can foster collective intelligence in human-AI collaboration that illuminates scientific reasoning, personalizes instruction, and supports students in developing robust scientific understandings for the twenty-first century.

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SCIENTIFIC CURIOSITY AND CRITICAL THINKING THROUGH SCIENTIFIC COLLABORATION: THE MODERATED MEDIATION ROLE OF SCIENTIFIC INQUIRY

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Abstract. *Although cognitive and social processes influencing students' scientific thinking skills have been extensively studied in recent years, the interplay between these processes remains insufficiently understood. This study examines the mediating role of research collaboration in the relationship between epistemic curiosity and critical thinking, as well as the moderating role of students' scientific inquiry skills in shaping these dynamics. Adopting a pragmatist paradigm, this research employs a mixed-methods research design, specifically an exploratory sequential design with a scale development component. The qualitative phase utilizes a case study design, incorporating in-depth interviews with teachers from science upper secondary in Mersin, Türkiye, to inform the theoretical framework for scale development. The quantitative phase applies a causal-comparative design, analyzing data from 371 teachers to test a moderated mediation model. The psychometric properties of the developed scale were rigorously assessed through content validity, construct validity, and reliability analyses, confirming its validity and reliability. Findings indicate that scientific collaboration significantly enhances the effect of scientific curiosity on critical thinking. However, the magnitude of this effect varies depending on students' scientific inquiry skills. Qualitative insights reveal that while teachers endorse student-centered approaches, they encounter challenges in implementing these methods effectively in classroom settings.*
Keywords: *critical thinking, scientific collaboration, scientific curiosity, scientific inquiry*

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Introduction

Rather than being limited to individual reasoning, scientific thinking emerges through the interplay between cognition and social context. This view is also reflected in prior research, which highlights that it is not merely the product of individual cognitive processes (Antink-Meyer et al., 2023) but also a multi-layered field of interaction shaped by the social context (Cottrell, 2023). In this context, scientific collaboration emerges as a fundamental learning dynamic that nurtures students' curiosity (Fair, 2023) and deepens their critical thinking skills (Haber, 2020). On the other hand, scientific curiosity triggers the individual's orientation toward the unknown (Ribosa & Duran, 2022; Willis & Willis, 2020) and search for meaning (Bjerknes et al., 2023); critical thinking ensures that this process progresses in a systematic, questioning, and reflective manner (Fasko & Fair, 2020). However, the effective development of these two skills often depends on the interactive opportunities provided by the learning environment (Paul & Elder, 2020) and how students connect with these opportunities (Nicolopoulou et al., 2021). At this point, scientific inquiry processes can be evaluated not only as a pedagogical method (Books, 2023; Mahat & Kandel, 2023; Singh et al., 2023) but also as a moderated mediation mechanism in understanding this relationship. Building on this, the present research aimed to examine the impact of scientific collaboration on students' scientific curiosity and critical thinking tendencies, and sought to elucidate, at both conceptual and empirical levels, how scientific inquiry assumed a contextual mediation role in this interaction.

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Literature Review

Not only cognitive skills (Dos Santos & Krause, 2017) but also social interaction dynamics (Dehghanzadeh et al., 2024) and affective characteristics (Chen et al., 2023) are decisive in students' orientation toward scientific thinking. In this context, scientific collaboration is a form of social interaction that transforms learning processes not only into sharing-based (Meyer et al., 2024) but also meaning-production-oriented ones (Feldman et al., 2024). At this point, Vygotsky's (1978) sociocultural theory emphasizes that the student's cognitive development is shaped through social interaction. Within the framework of this theory, scientific collaboration acts as a lever in realizing the student's cognitive potential (Abegglen et al., 2023). This is because collaborative learning processes enable not only the sharing of knowledge (Forbes, 2022) but also the comparison, structuring, and transformation of ways of thinking (Salmons, 2019). In this context, scientific curiosity and critical thinking emerge as the two fundamental mental tendencies in the student's approach to scientific knowledge (Bastianens et al., 2017; Hanscomb, 2023). Scientific curiosity encompasses the student's drive to explore the unknown, sensitivity to identifying gaps in understanding, and desire to discover (Dawson & Venville, 2022; Karwal et al., 2023); critical thinking is defined as the ability to question, justify, analyze, and reach consistent conclusions about information (Chatfield, 2022; Elder & Paul, 2020). The literature has frequently emphasized that these two tendencies reinforce each other in terms of cognitive flexibility and intellectual autonomy (Dave, 2024; Fury, 2024; Pu & Xu, 2023; Rousseau & van Gelder, 2024; Senent et al., 2021). However, the question of how the relationship between these two mental capacities is established highlights the importance of scientific collaboration as an explanatory variable. Collaboration diversifies cognitive stimuli among students (Muchie et al., 2024; Pu & Barnard, 2025) while also enabling the sharpening of curiosity through epistemic tensions and debates (Liu, 2020; Judijanto et al., 2025) and the strengthening of critical inquiry (Forman, 2020). However, it is evident that this relational structure is not one-dimensional but rather the product of a multi-layered mental activity. It is precisely at this point that scientific inquiry comes into play. Scientific inquiry refers to the student's active participation in the processes of systematically defining a scientific problem (Marco, 2025), developing hypotheses (Wulff, 2022), gathering evidence, and drawing conclusions (Bagdi et al., 2024). This process is not only a learning method but also provides a mental framework that shapes and guides the student's critical thinking (Bansal & Ramnarain, 2023; Concannon et al., 2020; Shearmur, 2020). In other words, scientific collaboration can only contribute significantly to critical thinking if students have effective inquiry practices (Book, 2024; Paavola & Shook, 2021). Therefore, the student's scientific inquiry capacity (Recker, 2021) should be considered a strategic variable that can determine the strength and direction of this relational line. Theoretically, this model overlaps with social cognition theory, constructivist learning theory, and the epistemic cognition approach. In particular, social cognitive theory argues that students' mental processes are shaped through interaction with others (Bandura, 1986), while the epistemic cognition approach (Greene et al., 2016) explains how students' beliefs about knowledge, the nature of knowledge, and the processes of knowing influence their critical thinking behaviors. The constructivist learning theory (De La Sienra, 2019) posits that students actively construct knowledge and that learning is shaped by experiences, social interactions, and prior knowledge. In this context, the theoretical axis of the research focuses on how students' higher-order cognitive tendencies, such as scientific curiosity and critical thinking, are shaped in a social context and through inquiry-based interaction (Madison, 2023; Pu & Xu, 2023). This approach makes it possible to understand not only individual but also collective cognitive capacities in today's complex information environments (Akpan et al., 2023; Nahar & Tayem, 2024). In light of all these theoretical perspectives, scientific curiosity, critical thinking, scientific inquiry, and scientific collaboration are interrelated concepts that are difficult to consider independently of one another. Scientific curiosity represents the internal motivation to learn and the desire to discover (Goodwin, 2020), while critical thinking provides a cognitive framework that enables this curiosity to be directed in a systematic and analytical manner (Kirk et al., 2023; Li, 2023). The relationship between these two tendencies is critical in terms of the student's intellectual depth and academic flexibility. At this point, scientific collaboration provides a social ground that encourages interaction among students, both keeping curiosity alive (Keengwe, 2022) and supporting the development of critical thinking (Fair, 2023). The theoretical proposition of the study is that scientific collaboration plays a mediating role between these two mental capacities. On the other hand, scientific inquiry is an important factor that determines the strength and direction of this association between scientific collaboration and critical thinking. Scientific inquiry, which refers to the student's active participation in scientific processes, is considered a regulatory variable that shapes this relationship. However, while research on the multi-layered cognitive and social processes that support students' scientific thinking capacities has increased in recent years (Butcher et al., 2023; Gai et al., 2022; Gyllenpalm et al., 2021; Hou et al., 2020; Kan et al., 2024; Kanyonga et al., 2024; Kirk et al., 2023; Lee & Haupt, 2020; Li et al., 2024; Liao

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& Yuan, 2024; McPhee & Cox, 2024; Orona & Pritchard, 2021; Schwarz et al., 2023; Shahriary et al., 2020), it has remained limited in developing comprehensive models explaining how these processes interact with one another. In particular, the question of how higher-order cognitive tendencies such as scientific curiosity and critical thinking are shaped in social learning environments and which mediating and moderating variables are effective in these processes (Chaparro-Banegas et al., 2024; Kenett et al., 2023; Li, 2023; Oberman, 2023; Pollarolo et al., 2022; Reed et al., 2024; Whitworth, 2025) has remained an unresolved gap in the literature. Current research has mostly addressed these concepts in isolation (Anupam, 2022; Butcher et al., 2023; Cook & Wheeler, 2023; Fan et al., 2023; Kenett et al., 2023; Li & He, 2022; Liao & Yuan, 2024; Ninos, 2023; Oberman, 2023; Pu & Xu, 2023; Rogante et al., 2021; Rousseau & van Gelder, 2024; Senent et al., 2021; Shellito, 2020; Su et al., 2017; Suwono et al., 2021; Whitworth, 2025); it has not developed a holistic view of the dynamic relationship between the student's orientation toward scientific knowledge, critical inquiry skills, and social interaction practices (Varlık, 2024; Varlık et al., 2024). In this context, it is important to reveal how scientific collaboration functions not only as a pedagogical strategy (Chen et al., 2023; Li & He, 2022; Rogante et al., 2021) but also how it functions as a social foundation that transforms students' cognitive tendencies (Fan et al., 2023; Lee & Haupt, 2020). Based on this, the fundamental rationale of the research was based on the assumption that scientific collaboration could play a mediating role in the association between scientific curiosity and critical thinking, and that the strength of this role might vary depending on the student's scientific inquiry capacity. Within this framework, the objective of the study was to reveal the moderated mediation role of scientific inquiry in the association between scientific curiosity and critical thinking through scientific collaboration. Thus, the aim of this study was to develop a deeper understanding of both the function of social interaction-based learning environments and the multidimensional nature of scientific thinking. In line with this objective, the research provides a framework for understanding how students' scientific curiosity and critical thinking tendencies are shaped in social interaction and inquiry-based learning environments. In particular, it seeks to explain how processes such as scientific collaboration and scientific inquiry are related to these two mental capacities. The findings may provide clues as to the conditions under which collaborative and inquiry-based approaches can be more effective in teaching programs. In this respect, the research offers content that can contribute to the design of learning environments, the development of teaching strategies, and the support of students' higher-order thinking skills. Additionally, by more clearly highlighting the role of social interaction and active participation in the development of scientific thinking, it contributes to a more holistic approach to the interrelationships between these concepts in educational research.

Research Questions

1) How do science teachers perceive and define the concepts of scientific curiosity, critical thinking, scientific collaboration, and scientific inquiry?
2) Does scientific inquiry have a moderated mediation role in the association between scientific curiosity and critical thinking through scientific collaboration?

Research Methodology

Design

The research is based on a pragmatic philosophical foundation that emphasizes the complementary power of both quantitative and qualitative approaches in knowledge production (Gunbayi & Sorm, 2020). In this regard, the research is structured within the framework of mixed-methods research (Mertens, 2023; Tashakkori et al., 2020) and adopts the scale development sub-design of the exploratory sequential design (Creswell & Guetterman, 2019; Fetters, 2020; Johnson & Christensen, 2020). The qualitative phase of the research was conducted according to the case study design, which aims to obtain contextual and in-depth data on students' scientific thinking processes (DeMarrais et al., 2024; Okoko et al., 2023). The findings obtained from this phase informed the scale development process and formed the basis for the quantitative dimension of the research. In the quantitative phase, causal comparative designs were used (Adams & McGuire, 2023; Blair et al., 2023; Crano et al., 2023) to test the relational structures between variables and analyze the developed model. This holistic approach ensured that the research was based on a more solid foundation at both the theoretical and practical levels. The theoretical design of the research is presented in Figure 1.

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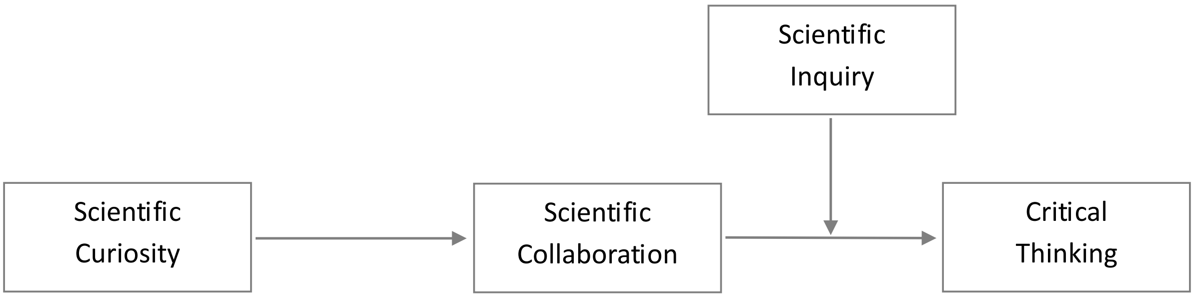
Figure 1
Theoretical Model



When the theoretical model of the study is examined in Figure 1, the interactions between students' scientific thinking processes can be seen. According to the model, scientific curiosity stands out as an internal source of motivation for learning in students and paves the way for scientific collaboration. In this collaborative environment, students interact with each other through idea exchange and joint problem-solving processes. This process directly supports the development of critical thinking. The model also shows that scientific inquiry plays a moderated mediation role in this association. In other words, the inquiry activities that students carry out during scientific collaboration serve as a decisive factor in the transition to critical thinking.

This research was planned and conducted between September 1, 2024, and July 21, 2025. In addition, ethical committee approval for the research was obtained with the decision of the Düzce University Scientific Research and Publication Ethics Committee dated July 3, 2025, and numbered 351.

Sampling

The qualitative phase of the study was conducted with seven teachers working at science upper secondary in Mersin, Türkiye. Criteria sampling was used to select participants in accordance with qualitative research methods (Cry & Goodman, 2024). In this context, the criteria for selecting teachers for the sample were "working in the fields of physics, chemistry, or biology; having a master's or doctoral degree in at least two of the variables such as scientific curiosity, scientific collaboration, critical thinking, or scientific inquiry; or having at least one article published in an ESCI or Q4 indexed journal in these fields at the international level." ESCI, or Q4-indexed journal in these fields" were used as criteria for teacher selection. This ensured that teachers who could best contribute to illuminating the research problem were included in the study. The quantitative phase of the research was conducted on the teacher population in the central districts of Mersin Province: Akdeniz, Toroslar, and Yenişehir. According to information obtained from the Strategy Development Unit of the Mersin Provincial Directorate of National Education, the study population comprised 11,090 teachers, stratified by district as follows: "Akdeniz 3,781, Toroslar 3,797, Yenişehir 3,512," with each stratum exhibiting a homogeneous structure within itself. Considering a 5% margin of error and a 95% confidence level (Hiebert et al., 2023), it was calculated that at least 371 teachers needed to be included in the study. In this regard, simple random sampling was applied proportionally to the total number of teachers in each district using stratified sampling (Zou & Xu, 2023), and a total of 371 teachers were included in the study: 126 from Akdeniz, 127 from Toroslar, and 118 from Yenişehir. In this way, the representativeness of each stratum was sought to be ensured in the study.

Data Collection Tools

In the first phase of the research, semi-structured in-depth interviews were conducted with seven teachers working at a science upper secondary and who are experts in their field, with the aim of thoroughly examining the nature and dimensions of the concepts of "scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry," which play an important role in science education. The qualitative data were systematically analyzed using a combination of thematic, descriptive, and content analysis techniques to provide a more comprehensive and nuanced understanding of the teachers' scientific thinking processes. Thematic analysis enabled the identification of recurring patterns and concepts across the data, descriptive analysis facilitated a detailed portrayal of participants' perspectives, and content analysis allowed for the quantification and systematic categorization of key

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ideas. Initially, the data were coded and subsequently grouped under common themes, ensuring both depth and rigor in the analysis. As a result of the analyses, four main factors supporting the theoretical basis of the research were identified, and these factors formed the conceptual framework for the scale development process. Draft scale items were developed based on the qualitative findings, and these items were evaluated by a panel of field experts (five academics and three practitioners) in terms of content validity, language validity, and criterion validity. After making the necessary revisions based on expert opinions, exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) were applied to test the construct validity of the scale. Finally, McDonald's Omega (ω) reliability coefficients were calculated to determine the internal consistency level of each factor.

In the exploratory factor analysis conducted to measure the scientific curiosity factor, 11 items were initially used. However, three items with low factor loadings and related to other factors were removed, and the analysis was completed with eight items. To examine the construct validity of the scientific curiosity factor, the suitability of the data set for factor analysis was first evaluated. The Kaiser-Meyer-Olkin (KMO) sample adequacy coefficient was calculated as .834, and the Bartlett's sphericity test result was found to be significant (χ^2 = 1710.88; $p < .001$). These findings indicate that the data are suitable for factor analysis (Finch, 2019). In the examination conducted with principal component analysis, eight items with factor loadings ranging from .757 to .856 were grouped under a single factor, and this structure explained 73.715% of the total variance. The high KMO value, significant Bartlett test, and high variance explanation ratio indicate that the scale exhibits a strong factorial structure (Finch, 2019; Garson, 2023; Mindrila, 2017). Subsequently, confirmatory factor analysis (CFA) was conducted to validate the obtained factor structure. When examining the model fit indices, the following values were obtained: χ^2/df = 1.376, $p > .001$, CFI = .999, TLI = .996, RMSEA = .032, and SRMR = .019. These results support the model's good fit (Kline, 2023; Newsom, 2023). To examine construct validity in more detail, convergent validity and composite reliability values were calculated. The average variance explained (AVE) was found to be .722, and this value, being above 0.50, indicates that the factor's convergent validity is established (Crano et al., 2023; Zou & Xu, 2023). The composite reliability (CR) coefficient was calculated as .934, indicating that the factor has high internal consistency (Adams & McGuire, 2023; Hiebert et al., 2023). Finally, McDonald's Omega (ω) coefficient was calculated to assess the reliability of the factor and was found to be .856. This value supports the consistent structure of the scientific curiosity factor (Cipresson & Immekus, 2022). All of these findings are based on the 8-item *"I-1. My students ask 'why' and 'how' questions about the topics they learn in class; I-2. My students try to understand the process behind an experiment or topic rather than memorizing the results; I-3. My students are curious about and question the scientific mechanisms behind ordinary events; I-4. My students generate hypotheses such as "What if we tried another method?" and seek different solutions; I-5. My students conduct in-depth research by relating the information they learn to their daily lives; I-6. My students take an active role in laboratory applications and are eager to discuss the results; I-7. My students are not satisfied with scientific topics and seek additional information from other sources (books, videos, articles); I-8. My students do not give up trying, even if they make mistakes and recognize the value of learning in the process."* This demonstrates that the scientific curiosity factor is a valid and reliable measurement tool.

In the exploratory factor analysis conducted to measure the scientific collaboration factor, nine items were initially used. However, one item with a low factor loading value and related to other factors was removed, and the analysis was completed with eight items. To examine the construct validity of the scientific collaboration factor, the suitability of the data set for factor analysis was first evaluated. The Kaiser-Meyer-Olkin (KMO) sample adequacy coefficient was calculated as .865, and the Bartlett's sphericity test result was found to be significant (χ^2 = 1515.554; $p < .001$). These findings indicate that the data are suitable for factor analysis (Mindrila, 2017). In the examination conducted with principal component analysis, eight items with factor loadings ranging from .791 to .846 were grouped under a single factor, and this structure explained 70.037% of the total variance. The high KMO value, significant Bartlett test, and high variance explanation ratio indicate that the factor exhibits a strong factorial structure (Finch, 2019; Garson, 2023; Mindrila, 2017). Subsequently, confirmatory factor analysis (CFA) was conducted to validate the obtained factor structure. When examining the model fit indices, the following values were obtained: χ^2/df = 1.335, $p > .001$, CFI = .999, TLI = .996, RMSEA = .030, and SRMR = .013. These results support the model's good fit (Hoyle, 2023). To examine construct validity in more detail, convergent validity and composite reliability values were calculated. The average variance explained (AVE) was found to be .672, and this value, being above 0.50, indicates that the factor's convergent validity is established (Crano et al., 2023; Zou & Xu, 2023). The composite reliability (CR) coefficient was calculated as .938, indicating that the factor has high internal consistency (Adams & McGuire, 2023; Hiebert et al., 2023). Finally, McDonald's Omega (ω) coefficient was calculated to assess the reliability of the factor and was found to be .874. This value supports the consistent structure of the scientific collaboration factor (Luhanga & Harbaugh, 2021). All of these findings are based on the 8 items comprising "*I-1. My*

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students actively exchange ideas in group work and value the opinions of others; I-2. My students successfully synthesize different perspectives by discussing a common scientific problem; I-3. My students contribute to a collective production process by sharing their knowledge and skills while working as a team; I-4. My students learn to draw on different fields by collaborating on interdisciplinary projects; I-5. My students defend their own ideas in group discussions while also demonstrating compromise skills; I-6. My students are aware that working together enriches scientific processes and embrace this approach; I-7. My students demonstrate a balanced ability to lead and be a team member when collaborating; I-8. My students value collective success over individual success and are motivated by achieving results as a team." This demonstrates that the scientific collaboration factor is a valid and reliable measurement tool.

In the exploratory factor analysis conducted to measure the critical thinking factor, nine items were initially used. However, two items with low factor loadings and related to other factors were removed, and the analysis was completed with seven items. To examine the construct validity of the critical thinking factor, the suitability of the data set for factor analysis was first evaluated. The Kaiser-Meyer-Olkin (KMO) sample adequacy coefficient was calculated as .848, and the Bartlett's sphericity test result was found to be significant (χ^2 = 1244.998; p < .001). These findings indicate that the data are suitable for factor analysis (Garson, 2023). In the analysis conducted using principal component analysis, seven items with factor loadings ranging from .771 to .862 were grouped under a single factor, and this structure explained 70.629% of the total variance. The high KMO value, significant Bartlett test, and high variance explanation ratio indicate that the factor exhibits a strong factorial structure (Finch, 2019; Garson, 2023; Mindrila, 2017). Subsequently, confirmatory factor analysis (CFA) was conducted to validate the obtained factor structure. When examining the model fit indices, the following values were obtained: χ^2/df = 2.240, p > .001, CFI = .997, TLI = .983, RMSEA = .058, and SRMR = .018. These results support the model's good fit (Verma & Verma, 2024). To examine construct validity in more detail, convergent validity and composite reliability values were calculated. The average variance explained (AVE) was found to be .654, and this value, being above 0.50, indicates that the factor's convergent validity is established (Crano et al., 2023; Zou & Xu, 2023). The composite reliability (CR) coefficient was calculated as .940, indicating that the factor has high internal consistency (Adams & McGuire, 2023; Hiebert et al., 2023). Finally, McDonald's Omega (ω) coefficient was calculated to assess the reliability of the factor and was found to be .867. This value supports the consistent structure of the critical thinking factor (Sorgente et al., 2025). All of these findings are consistent with the 7-item *"I-1. My students question the information they encounter by asking questions such as "Is this true?" or "Could there be another explanation?"; I-2. My students analyze the basis and evidence when evaluating the validity of an idea; I-3. My students critically evaluate their own ideas and the views of others for consistency; I-4. My students actively use critical thinking skills when testing hypotheses in laboratory work; I-5. My students produce alternative solutions by reinterpreting information rather than passively receiving it; I-6. My students can identify contradictions and possible biases by looking at events from different perspectives; I-7. My students remain respectful while engaging in critical inquiry and make this approach a scientific habit."* This demonstrates that the critical thinking factor is a valid and reliable measurement tool.

In the exploratory factor analysis conducted to measure the scientific inquiry factor, 13 items were initially used. However, three items with low factor loadings and related to other factors were removed, and the analysis was completed with 10 items. To examine the construct validity of the scientific inquiry factor, the suitability of the data set for factor analysis was first evaluated. The Kaiser-Meyer-Olkin (KMO) sample adequacy coefficient was calculated as .930, and the Bartlett's sphericity test result was found to be significant (χ^2 = 6026.620; p < .001). These findings indicate that the data are suitable for factor analysis (Mindrila, 2017). In the examination conducted with principal component analysis, 10 items with factor loadings ranging from .740 to .855 were grouped under a single factor, and this structure explained 66.177% of the total variance. The high KMO value, significant Bartlett test, and high variance explained ratio indicate that the factor exhibits a strong factorial structure (Finch, 2019; Garson, 2023; Mindrila, 2017). Subsequently, confirmatory factor analysis (CFA) was conducted to validate the obtained factor structure. When examining the model fit indices, the following values were obtained: χ^2/df = 3.136, p > .001, CFI = .997, TLI = .984, RMSEA = .076, and SRMR = .015. These results support the model's good fit (Roos & Bauldry, 2021). To examine construct validity in more detail, convergent validity and composite reliability values were calculated. The average variance explained (AVE) was found to be .662, and this value, being above 0.50, indicates that the factor's convergent validity is established (Crano et al., 2023; Zou & Xu, 2023). The composite reliability (CR) coefficient was calculated as .947, indicating that the factor has high internal consistency (Adams & McGuire, 2023; Hiebert et al., 2023). Finally, McDonald's Omega (ω) coefficient was calculated to assess the reliability of the factor and was found to be .943. This value supports the consistent structure of the scientific curiosity factor (Cipresson & Immekus, 2022). All of these findings are based on the 10-item scale: *"I-1. My students generate questions through observation and investigate these questions using the scientific method; I-2. My students can formulate testable hypotheses about*

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topics that interest them; I-3. My students design and conduct appropriate experiments to test their hypotheses; I-4. My students analyze experiment results and make valid inferences; I-5. My students behave systematically in collecting and recording data during the research process; I-6. My students are not afraid of making mistakes when conducting scientific inquiry and see errors as learning opportunities; I-7. My students produce creative solutions by trying different approaches to solve a problem; I-8. My students understand the importance of each step in the scientific process (observation, hypothesis, experiment, conclusion); I-9. My students are unbiased and objective when evaluating research results; I-10. My students apply their scientific inquiry skills to everyday problems." This demonstrates that the scientific inquiry factor is a valid and reliable measurement tool.

Data Analysis

In the qualitative phase of this study, the theme proposed by Günbayı (2023) was adopted, along with descriptive and content analysis techniques. NVIVO 14 software was used to systematically analyze the data, and the reliability of the analyses was ensured by evaluating the consistency of the coding in accordance with the opinions of three independent field experts. The reliability value of [$K = .911$, $p = .001$] calculated using Fleiss's Kappa coefficient revealed a statistically significant agreement among coders and that the analysis results were highly reliable (Gwet, 2021). Participants' identities were anonymized using the letters A-G to protect their privacy. In the quantitative phase of the study, Model 14, developed by Hayes (2018), was used as a basis, and the analyses were performed using the PROCESS macro 5.0 program. Prior to the analysis, multivariate statistical assumptions were rigorously tested. The VIF values examined to control for multicollinearity ranged from 1.827 to 3.319 (all < 5), and the Durbin-Watson coefficient was found to be 2.109, indicating the absence of linearity issues and autocorrelation, respectively (Blair et al., 2023; Crano et al., 2023). Additionally, the skewness (−0.536 to −0.387) and kurtosis (−0.011 to +0.008) values remaining within the ±2 limits supported that the data met the assumption of multivariate normal distribution (Hiebert et al., 2023; Zou & Xu, 2023). In the study, "Scientific Curiosity" (X) was integrated into the model as an exogenous variable, "Scientific Collaboration" (M) as an instrumental variable, "Critical Thinking" (Y) as an endogenous variable, and "Scientific Inquiry" (W) as a moderating variable. This structure allowed for the simultaneous examination of mediating and moderating effects. Bootstrap analyses were conducted with 5,000 samples at a 95% confidence level, and the significance of indirect effects was evaluated through confidence intervals, providing strong evidence to support the robustness of the model.

Research Results

Qualitative Results

The themes, categories, and codes related to how teachers perceive and define the concepts of scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry are presented in Tables 1, 2, 3, and 4.

Table 1
Themes, Categories, and Codes Related to the Concept of Scientific Curiosity

Theme	Category	Code	Participants
Definition and Function	Initiator of the Scientific Process	Inquiry that begins with curiosity; why–how questions; desire to acquire knowledge	A, B, D, G
	Trigger for Deep Learning	Not remaining on the surface of knowledge; conducting research, making sense of knowledge	A, B, C, D
	Foundation of Scientific Thinking	Focusing on processes such as experimentation, observation, and hypothesis; moving away from memorization	B, E, F
Individual Development and Learning Process	Motivation and Intrinsic Drive	Intrinsic desire to learn; curiosity motivating the individual to take action	C, E
	Self-Directed Learning	Independent research; trying new approaches; independent learning	A, F, G
	Self-Confidence and Problem-Solving Skills	Development of self-confidence through questioning; creative and solution-oriented thinking	F, G

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Theme	Category	Code	Participants
Educational and Pedagogical Dimension	Laboratory and Applied Learning	The impact of curiosity in experiments; being more active in practical processes	B, E
	Support for Critical Thinking	Moving away from rote learning; generating alternative ideas	D, G
	Teacher Observation and Assessment	The curious student being noticed and encouraged by the teacher	C, F

When Table 1 is examined, it is seen that scientific curiosity plays a multi-layered and effective role in both individual development and scientific thinking. Within the scope of the theme of definition and function, the participants' statements reveal that curiosity is not just a temporary interest, but a fundamental cognitive and emotional dynamic that initiates, sustains, and directs the process of acquiring knowledge. Curiosity is not merely a desire to know, but also an effort to delve into the foundations of knowledge, question its rationale, and make sense of it. In this sense, it transforms the student from a passive recipient into an active learner. As the initiator of the scientific process, curiosity awakens the desire to question cause-and-effect relationships in individuals and, in this sense, triggers the desire to acquire knowledge. According to the participants' views (A, B, D, G), this type of questioning process ensures that students act not only with the intention of acquiring knowledge but also with the intention of producing knowledge. In this context, curiosity is not merely a superficial interest; it is a cognitive tool that encourages in-depth learning. Indeed, the statements of participants A, B, C, and D emphasize that the quality of learning is enhanced by not remaining on the surface of knowledge, but rather by conducting research and engaging in a process of interpretation. Curiosity also increases the orientation towards processes such as experimentation, observation, and hypothesis formation, which form the basis of scientific thinking (B, E, F), distancing the student from a rote approach and directing them towards critical thinking. In this respect, curiosity has a pedagogically transformative function beyond being a mere cognitive stimulus. When evaluated in terms of the theme of individual development and the learning process, it is understood that curiosity is an internal source of motivation and triggers the individual's self-regulatory behaviors toward learning. As emphasized by participants C and E, the inner desire to learn motivates the student, while participants A, F, and G state that this process strengthens self-directed learning behaviors and develops the student's ability to conduct independent research. In this context, self-confidence and problem-solving skills developed through asking questions and trying new approaches (F, G) contribute to the student's development as a more creative and solution-oriented individual in both their academic and personal lives. In terms of educational and pedagogical themes, the impact of curiosity on the learning environment is noteworthy. In particular, it has been observed that curiosity makes students more active and makes learning experiential (B, E), especially in laboratory and applied processes. In addition, as noted by participants D and G, curiosity supports critical thinking and enables the development of alternative ways of thinking. Finally, in the teacher observation and evaluation dimension, the views shared by participants C and F indicate that when a curious student is noticed and encouraged by the teacher, it positively impacts the learning process. The participants' views are provided below.

> [...] Scientific curiosity begins when students question a situation they encounter. Asking questions such as why, how, and when is the first sign of this curiosity. Curious students do not just listen to the lesson; they research and try to access different sources. This makes learning permanent and meaningful [A].

> [...] For me, scientific curiosity is a desire to delve into the background of knowledge. Students are curious not only about the result but also about the process. For example, instead of memorizing the result of an experiment, asking "Why did this result come out this way?" is a sign of scientific curiosity. This type of curiosity forms the basis of scientific thinking [B].

> [...] Scientific curiosity is an innate urge to understand nature. It is related to the desire to learn the mechanisms behind seemingly ordinary events. Curious students ask more questions and are not easily satisfied, which deepens the learning process. Seeing this in students really motivates me [C].

> [...] When a student asks questions such as "Why is it like this?" or "What would happen if it were different?" on a subject, it is a clear sign of scientific curiosity. Such questions move them away from rote learning and help them develop their own thought systems. Scientific curiosity is not just about knowing, but about trying to understand. This also brings critical thinking [D].

> [...] I believe that scientific curiosity is the driving force behind learning. Curious students read more, try more, make mistakes, but do not give up. In this process, they both develop themselves and discover the nature of science. The difference between curious students and others is particularly evident in laboratory applications [E].

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> [...] Scientific curiosity is when a student is not satisfied with a subject and wants more. A student who asks, "Is there another way to do this?" has taken the first step toward scientific thinking. Science cannot develop without curiosity, because every discovery begins with a question. That is why I value students who ask questions and question things in class [F].

> [...] When a student asks, "Why are we doing it this way?" or "What if we tried something else?", it is the most beautiful example of scientific curiosity. Such questions make learning active. Scientific curiosity is not just about acquiring knowledge, but about searching for new ways with that knowledge. This approach also develops the student's self-confidence and problem-solving skills [G].

When participants' statements are examined, it is seen that there is a common understanding of the role of scientific curiosity in the student's learning process, but this understanding is expressed in various dimensions. All participants define scientific curiosity as a driving force that goes beyond superficial knowledge acquisition and encourages deep thinking. For example, participants A and B emphasize that curiosity transforms the student into an active learner who does not settle for mere information but questions the process and cause-and-effect relationships. Participant C, on the other hand, defines this approach as an internal desire to explore nature and events, noting that curiosity deepens the learning process. Participants D and F view curiosity as an element that moves away from rote learning and supports questioning, thinking, and the search for meaning, particularly highlighting its role in the development of the student's own thought system. Participant E describes curiosity as the "driving force" of learning, emphasizing the student's development through trial and error, while participant G underscores that scientific curiosity involves not only acquiring knowledge but also creatively seeking new paths with that knowledge and solving problems. When these statements are evaluated together, it becomes clear that scientific curiosity is a multidimensional structure that meaningfully nourishes the student's intellectual development, critical thinking skills, motivation to learn, and participation in scientific processes.

Table 2
Themes, Categories, and Codes Related to the Concept of Scientific Collaboration

Theme	Category	Code	Participants
Definition and Function	Shared Goals and Ideas	Working together toward a common goal; sharing knowledge, contributing to each other	A, D, F
	Diversity and Richness of Perspectives	Different perspectives; achieving stronger results together	B, C, G
	Interdisciplinary Interaction	Drawing from different fields; thinking in a multifaceted way, intellectual diversity	C, G
Individual and Social Development	Empathy, Respect, and Humility	Empathy; valuing others' ideas, recognizing one's identity in collaboration	B, E
	Social and Scientific Responsibility	Taking responsibility; awareness of collective production, focusing on collective success	D, F
	Personal Contribution and Learning	Expressing one's own ideas; learning from others, collaboration as an opportunity for development	A, E
Educational and Scientific Process	Scientific Application Practice	The working style of real scientists; discussion, compromise, and collaborative production	D, F, G
	Teamwork and Skill Development	Interaction within the team; direct development of scientific skills, lifelong gains	G, B

When Table 2 is examined, it is understood that collaboration-based learning offers a strong structure in student development in both individual and collective terms. In terms of definition and function, collaboration is not just an activity carried out together; it is defined as the sharing of ideas, the exchange of information, and the deepening of learning through mutual contribution toward a common goal (A, D, F). In particular, the emphasis on diversity and richness of perspective (B, C, G) enables students to broaden their horizons by encountering different points of view and to achieve stronger results together. Interdisciplinary interaction (C, G) enables students to experience intellectual diversity by drawing on different fields, turning them into well-rounded individuals. In the context of individual and social development, values such as building empathy among students, respecting others' ideas, and sharing ideas with humility (B, E) are seen to provide important gains in terms of social learning.

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In this process, students develop not only academic skills but also social responsibility and a sense of collective production (D, F). According to the participants' statements, collaborative work supports students in recognizing their own contributions, freely expressing their ideas, and demonstrating personal development by learning from others (A, E). When evaluated in terms of educational and scientific processes, it is understood that students experience scientific practices not only theoretically but also practically and collaboratively (D, F, G). Discussion, compromise, and collaborative production enable students to learn in an environment similar to that of real scientific communities. In addition, teamwork (G, B) contributes not only to the development of academic skills but also to the development of communication, coordination, and lifelong collaboration skills. In short, collaboration among students emerges as an element that enriches learning not only in terms of knowledge transfer but also in many areas such as critical thinking, taking social responsibility, and active participation in scientific production. The participants' views are presented below.

> [...] Scientific collaboration is working together to exchange ideas toward a common goal. Students share their knowledge within the group and take into account the contributions of others, which creates this process. This type of interaction enriches learning and develops social skills. Science does not progress alone, but rather through collective thinking [A].

> [...] For me, scientific collaboration is about bringing together different perspectives to achieve stronger results. When students discuss a problem, they learn from each other and develop their own ideas. This process teaches not only knowledge but also empathy and patience. A scientific process without collaboration is incomplete [B].

> [...] Scientific collaboration is the process of combining the knowledge, experience, and skills of multiple individuals. This is not merely a division of labor; it is also a process of thinking and creating together. Students learn to draw from different fields, thereby developing an interdisciplinary perspective [C].

> [...] The foundation of scientific collaboration is students discussing, defending their ideas, and ultimately reaching a common solution while working together. This is very valuable in terms of both academic and personal development. In addition, the satisfaction of producing something together encourages them to do more research. Scientists do the same [D].

> [...] In my opinion, scientific collaboration means not being limited to individual knowledge, but being open to thinking together. Collaboration allows students to recognize their own contributions and shows them that there is much to learn from others. This brings humility and sharing. It teaches students that science is a collective process [E].

> [...] Scientific collaboration is formed when multiple students work toward a common goal and take responsibility. In this process, students both express their own ideas and learn to listen to others. Scientific collaboration emphasizes collective success over individual success. This is how things work in the real world of science [F].

> [...] Scientific collaboration is a productive process that brings together different talents. It is not just about working together; it is about understanding, agreeing, and coming to a common understanding. The interaction that students demonstrate while working in teams directly develops their scientific skills. These skills accompany them throughout their lives [G].

When the participants' statements are examined, it is evident that there is a strong and multidimensional common understanding of scientific collaboration. All participants do not view scientific collaboration as merely working together; rather, they define it as a productive and transformative process based on the exchange of ideas. Participant A approaches collaboration in terms of knowledge sharing and the development of social skills, emphasizing that science is inherently a collective process. Participant B evaluates this process as a means of blending different perspectives to achieve higher-quality outcomes, while also emphasizing that emotional skills such as empathy and patience are developed through collaboration. Participant C interprets scientific collaboration through interdisciplinary interaction and defines this process as "thinking and producing together," pointing to a deep cognitive contribution. Participant D focuses on the processes of joint discussion, defending ideas, and producing common solutions among students, emphasizing that this interaction is important for both academic and personal development. Participant E addresses collaboration in the context of the collective nature of knowledge, noting that the process encourages humility and a culture of sharing among students. Participant F states that scientific collaboration requires taking responsibility in line with common goals, emphasizing collective success over individual success. Participant G defines collaboration not only as a technical division of labor but also as a process based on understanding, compromise, and collective reasoning, noting that this process contributes to students' scientific skills and long-term development. When all these views are considered together, scientific collaboration emerges not merely as an academic task but as a holistic form of interaction that transforms students cognitively, emotionally, and socially, bringing them closer to the true nature of science.

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Table 3
Themes, Categories, and Codes Related to the Concept of Critical Thinking

Theme	Category	Code	Participants
Definition and Function	Questioning and Evaluating Information	Not accepting information at face value; questioning, evaluating sources	A, B, D, F
	Analytical and Independent Thinking	Critical reasoning; developing independent thinking	B, D, E
	Reconstructing Information	Questioning the source and validity of information; producing information	E, F
Application and Skills	Hypothesis Testing and Scientific Applications	Testing hypotheses; laboratory applications; verifying information	C, F
	Alternative Solutions and Multifaceted Perspectives	Being able to see things from different perspectives; recognizing contradictions, alternative solutions	G, C
Individual Development and Impact	Mental Independence and Critical Awareness	Questioning one's own thoughts; mental independence, being a free individual	D, G
	The Importance of Critical Thinking in Education	The importance of fostering critical thinking; its critical role in the learning process	E, F

When Table 3 is examined, it is seen that critical thinking skills play a fundamental role in the student's learning process in terms of both cognitive and personal development. Within the scope of the definition and function theme, it is important for students not to accept information as it is, but to question it, evaluate its basis, and approach it with a critical distance (A, B, D, F). In this process, the student becomes not only a consumer but also a subject who reconstructs and produces knowledge (E, F). Analytical and independent thinking skills (B, D, E) enable the student to form their own thought system and reach independent judgments through critical reasoning. In the theme of application and skills, it is noteworthy how critical thinking is combined with concrete scientific processes. In particular, hypothesis testing and laboratory applications (C, F) enable students to develop their ability to verify information and participate directly in scientific processes, making their ideas testable. The ability to generate alternative solutions and develop a multifaceted perspective (G, C) enables students to see different points of view, recognize contradictions, and develop more flexible and creative solutions. In this respect, critical thinking is reflected in students not only as a theoretical but also as an applied skill. In the context of individual development and impact, it is noteworthy that students gain mental independence (D, G) and develop intellectual awareness by questioning their own thoughts. This contributes to students constructing their own thought structures as free and responsible individuals. Similarly, the place of critical thinking in the educational process (E, F) reveals that this skill is an indispensable tool not only in terms of individual development but also in terms of improving the quality of learning. The participants' statements reflect a common approach that the acquisition of critical thinking should be one of the fundamental goals of education. In short, critical thinking transforms students into active subjects who not only access knowledge but also structure it; who not only learn but also question and guide their learning. In this sense, critical thinking is considered a central skill that nourishes student development in both scientific and educational contexts. The participants' views are presented below.

> *[...] Critical thinking is the ability to question information rather than accepting it at face value. The student's thinking, "Is this correct? Could there be another explanation?" is the beginning of this process. This way of thinking enables true learning by avoiding rote memorization. Progress in science also begins with this questioning [A].*

> *[...] For me, critical thinking is the process of evaluating the basis of an idea before blindly accepting it. Students do not just look for the right answer, they also try to understand why the information given is correct. This develops both analytical and independent thinking. This is the cornerstone of scientific reasoning [B].*

> *[...] A critically thinking student questions both their own ideas and those of others. This questioning is not disrespectful; it is a way of verifying information. Testing hypotheses, especially in laboratory work, is an application of this skill. This competence distances the student from superficial thinking [C].*

> *[...] Critical thinking is the student's analysis of the information they encounter rather than immediately believing it, evaluating its consistency. They question not only what the teacher says but also what goes through their own mind. This increases the individual's mental independence. Critical thinking is a fundamental characteristic of free and scientific individuals [D].*

> *[...] In my opinion, critical thinking is the courage to not settle for information but to reconstruct it. Students question both the source and validity of information. This transforms them from mere consumers of information into producers of information. It is very important to impart this skill in education [E].*

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[...] Critical thinking is not accepting everything one hears as true but seeking evidence. The student's skeptical approach to information leads to new questions and deeper research. This approach also plays a fundamental role in the development of science. It is very valuable to see this awareness in students [F].

[...] Critical thinking involves being able to look at events from different angles and recognize contradictions. A student who can think of not just one solution, but alternative solutions has acquired this skill. This advances them both academically and in terms of life skills. A critical perspective is the spirit of scientific progress [G].

When the participants' statements are examined, it is understood that critical thinking is seen as an indispensable skill in the student's intellectual development and scientific learning process. The main point on which the participants agree is that critical thinking is not only a process of questioning knowledge but also brings with it mental independence, in-depth learning, and scientific productivity. Participant A defines this skill as the student's questioning of knowledge rather than accepting it directly, noting that it moves away from a rote approach and forms the basis of scientific progress. Participant B defines critical thinking as the process of analyzing and understanding the reasons behind an idea, emphasizing that it develops analytical thinking and independent decision-making skills. Participant C emphasizes that this skill involves questioning not only the ideas of others but also one's own ideas, and states that this process is concretized in the laboratory environment through hypothesis testing. Participant D relates critical thinking to the individual's mental freedom, arguing that the process of evaluating both external and internal sources of information brings the student closer to the identity of a free individual. Participant E views critical thinking not only as approaching knowledge with skepticism, but also as the courage to reconstruct knowledge, noting that this process transforms students from knowledge consumers to knowledge producers. Participant F similarly states that a skeptical approach deepens the search for knowledge and that this awareness is essential for scientific development. Participant G associates critical thinking with the ability to develop a multifaceted perspective and recognize contradictions, emphasizing that this ability contributes not only to the student's academic capacity but also to their ability to solve problems in life. When these statements are evaluated as a whole, critical thinking emerges as a multidimensional mental competence that enables students to go beyond passively receiving information and engage in an active, questioning, and productive learning process.

Table 4
Themes, Categories, and Codes Related to the Concept of Scientific Inquiry

Theme	Category	Code	Participants
Definition and Function	Fundamentals of the Scientific Process	Observing, asking questions, forming hypotheses, and testing them	A, C, D, F, G
	Active and Effective Learning	Not being a passive recipient; taking on the role of researcher, active learning	A, C, D
	Trial and Error and Patience	Not being afraid of making mistakes; systematic testing, patience, and attention to detail	B, E, G
Personal Development and Responsibility	Conscious and Methodical Work	Systematically questioning information; conscious and methodical work	E, F
	Independence and Responsibility	Taking responsibility for learning; independent thinking and decision-making	F, G
Scientific Approach and Skills	Evidence-Based Assessment	Decision-making based on evidence; forming hypotheses, conducting experiments, and evaluating results	G, A, F
	Multifaceted and Systematic Thinking	Systematic and multifaceted thinking; thinking like a scientist	G, E

When Table 4 is examined, it is seen that scientific thinking skills are reflected in the student's learning process in an effective and transformative way. Within the scope of the definition and function theme, it is understood that the student experiences the scientific process not only as a theoretical set of knowledge but also as active research processes such as observing, asking questions, forming hypotheses, and testing (A, C, D, F, G). In this way, the student moves away from the role of a passive recipient of knowledge and takes on the identity of a researcher, becoming a subject who participates in, questions, and produces the process (A, C, D). In addition, the trial-and-error approach and patience-requiring stages involved in the scientific process (B, E, G) support the student in overcoming their fear of making mistakes, progressing systematically, and developing careful observation skills.

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Within the framework of individual development and responsibility, it is observed that students go beyond superficial acquisition of knowledge and develop the habit of conscious and methodical questioning (E, F). This habit not only enables students to access knowledge but also to take responsibility for their own learning process. As emphasized by participants F and G in particular, this process enables students to think independently, develop their decision-making skills, and adopt a more autonomous attitude toward learning. Within the theme of scientific approach and skills, it is observed that students focus on evidence-based thinking in the scientific process (G, A, F). Through processes such as hypothesis formation, experimentation, and evaluation of results, students do not merely learn information; they test, evaluate, and ground it in solid foundations. As emphasized in the statements of participants G and E, this process develops systematic and multifaceted thinking skills in students, enabling them to think like scientists. In short, these findings show that students internalize scientific thinking not only as a content area but also as a mental attitude and learning strategy. In this respect, science process-based learning transforms into a multidimensional learning experience that empowers students both cognitively and personally. The participants' statements are provided below.

[...] Scientific inquiry is the process of asking questions based on observations, forming hypotheses, and testing these hypotheses. Students should be curious not only about the result but also about the path leading to that result. In this process, they conduct experiments, collect data, and make inferences. In other words, scientific inquiry is active learning itself [A].

[...] For me, scientific inquiry is the process of investigating why and how knowledge is formed. Students identify a problem, think about possible solutions, and test them. They are not afraid of making mistakes because the nature of inquiry is trial and error. This is the fundamental way science progresses [B].

[...] Scientific inquiry is a process in which the student is not a passive recipient but an active researcher. The first step in this process is to try to establish a cause-and-effect relationship in response to an event. Then they observe, develop hypotheses, and design experiments. In this way, they learn all the steps of the process of acquiring knowledge [C].

[...] The scientific inquiry process begins with the student asking, "Why did this happen?" Then comes the question, "How can I test this?" These two questions already introduce them to the scientific way of thinking. I see that when students acquire this approach, they achieve deeper and more lasting learning [D].

[...] I believe that scientific inquiry is a process that progresses alongside critical thinking. It means not only questioning a piece of information but also trying to test it systematically. Students who understand this process work more consciously and methodically. They also become more patient and attentive [E].

[...] Scientific inquiry is the process of producing explanations for an event observed by the student and testing these explanations. This process encompasses the basic steps of the scientific method. When students acquire this skill, they begin to take responsibility for their own learning. Independence in science stems from this [F].

[...] Scientific inquiry requires deciding what is true not from outside sources but through evidence. The student formulates a hypothesis, conducts an experiment, and evaluates the results. This process forces them to think systematically, be patient, and look at things from multiple perspectives. This is the most concrete example of thinking like a scientist [G].

When participants' statements are examined, it is understood that scientific inquiry is seen as a fundamental learning process that transforms students from passive recipients of information into active and systematic producers of knowledge. All participants agree that scientific inquiry not only provides access to knowledge but also contributes directly to the development of cognitive skills, the assumption of responsibility for learning, and the process of thinking scientifically. Participant A defines this process as the essence of active learning, consisting of the steps of observation, hypothesis formation, and testing; participant B views scientific inquiry as a trial-and-error process and emphasizes that students should seek solutions without fear of making mistakes. Participant C states that scientific inquiry transforms students into researchers and that learning deepens as students experience all the steps of acquiring knowledge. Participant D focuses on the fundamental questions that trigger this process – "Why did this happen?" and "How can I test this?" – and states that this inquiring approach leads to lasting learning. Participant E emphasizes that scientific inquiry is an integrated process with critical thinking, stating that students who are familiar with this method work more systematically, carefully, and patiently. Participant F evaluates this process within the framework of the basic steps of the scientific method and states that scientific inquiry develops learning responsibility and independence in students. Participant G similarly states that scientific inquiry is not only about acquiring knowledge but also about reaching the truth through evidence, and that this process encourages students to think in a multifaceted, patient, and systematic way. When these statements are evaluated together, scientific inquiry emerges as the most concrete and functional form of scientific thinking, supporting both the cognitive and emotional development of students and nurturing qualities such as systematic thinking, evidence-based reasoning, and responsibility for learning.

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Quantitative Results

The results of the correlation analysis regarding scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry are presented in Table 5, while the results of the analysis regarding the moderated mediation role of scientific inquiry in the association between scientific curiosity and critical thinking through scientific collaboration are presented in Table 6.

Table 5
Distribution Levels of Measurement Tools

Scales	*X*	*M-*	*Y*	*W*	*M*	SD
Scientific Curiosity (X)	1				3.60	0.79
Scientific Collaboration (M-)	.815**	1			3.69	0.75
Critical Thinking (Y)	.858**	.884**	1		3.58	0.81
Scientific Inquiry (W)	.624**	.654**	.690**	1	3.53	0.90

*$p < .05$; **$p < .01$; ***$p < .001$, N = 371 teachers participated in the survey.

When Table 5 is examined, it can be seen that there are strong and significant positive correlations between students' scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry scores. As scientific curiosity increases, students' tendencies toward scientific collaboration ($r = .815$, $p < .001$) and critical thinking ($r = .858$, $p < .001$) also rise; similarly, the association between scientific curiosity and scientific inquiry is also significant ($r = .624$, $p < .001$). The association between students' scientific collaboration and critical thinking scores is quite high ($r = .884$, $p < .001$), suggesting that collaborative work experiences may support depth of thinking. Additionally, the significant correlations between scientific collaboration and scientific inquiry ($r = .654$, $p < .01$) and between critical thinking and scientific inquiry ($r = .690$, $p < .001$) imply that students actively participate in the processes of discussing, questioning, and restructuring knowledge. When looking at the average values, the highest score belongs to the scientific collaboration variable ($M = 3.69$, $SD = 0.75$), followed by scientific curiosity ($M = 3.60$, $SD = 0.79$), critical thinking ($M = 3.58$, $SD = 0.81$), and scientific inquiry ($M = 3.53$, $SD = 0.90$); all standard deviations being below 1 indicate that the scores are relatively homogeneously distributed.

Table 6
Moderated Mediation Effect of Scientific Inquiry

Variables	Scientific Collaboration (M)			Critical Thinking (Y)		
	β	LLCI	ULCI	β	LLCI	ULCI
Scientific Curiosity (X)	.803***	.745	.862	.388***	.314	.463
Scientific Collaboration (M)	-	-	-	.513***	.434	.592
Scientific Inquiry (W)	-	-	-	.123***	.075	.172
M*W (Interaction)	-	-	-	.046***	.008	.084
R^2	.664			.851		
Indirect Effect*				-	-	-
Low Scientific Inquiry	.379***	.256	.518	-	-	-
Medium Scientific Inquiry	.412***	.293	.550	-	-	-
High Scientific Inquiry	.445***	.324	.584	-	-	-
Moderated Mediation Index	.037***	.010	.064			

Notes: *$p < .05$; **$p < .01$; ***$p < .001$ N = 371 teachers participated in the survey. [Scientific Curiosity→ Scientific Collaboration → Critical Thinking]*, LLCI = Sub-Confidence Interval; ULCI= Upper Confidence Interval.

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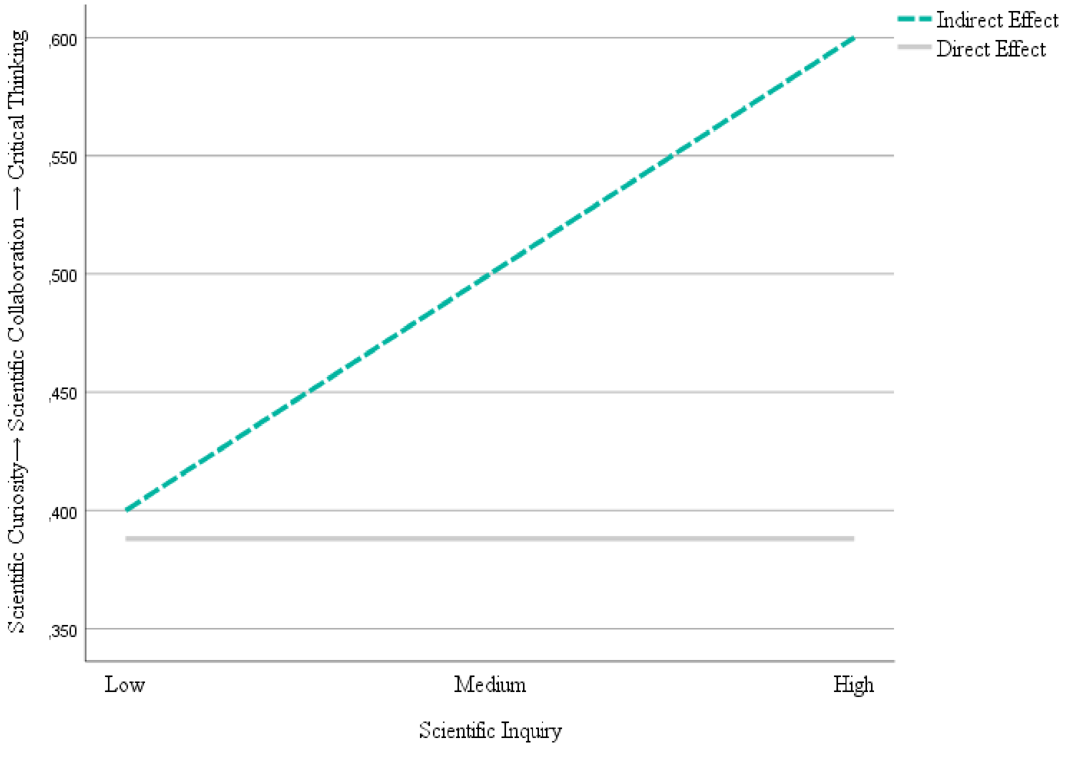
When Table 6 is examined, it is seen that students' levels of scientific curiosity significantly predict both scientific collaboration (β = .803, $p < .001$) and critical thinking skills (β = .388, $p < .001$). Furthermore, scientific collaboration is also a significant predictor of critical thinking (β = .513, $p < .001$). These findings indicate that students' scientific curiosity is not merely an individual trait but also shapes both their tendency to collaborate and their capacity for critical thinking. The scientific inquiry variable in the model also has a significant and positive direct effect on critical thinking (β = .123, $p < .001$). Furthermore, the interaction term between scientific collaboration and scientific inquiry is also significant (β = .046, $p < .001$); this indicates that the effect of scientific collaboration on critical thinking varies depending on the student's level of scientific inquiry. When examining the explanatory power of the model, high R^2 values of .664 for explaining scientific collaboration and .851 for explaining critical thinking were obtained, indicating that the model is quite robust. When examining conditional indirect effects, the indirect effect from scientific curiosity to critical thinking was β = .379, $p < .001$ for students with low scientific inquiry levels; β = .412, $p < .001$ for students with moderate levels; and β = .445, $p < .001$ for students with high levels. These results reveal that as the level of scientific inquiry increases, the indirect effect of scientific curiosity on critical thinking also strengthens. Finally, the "moderated mediation index" β = .037, CI [.010, .064] was found to be statistically significant. This finding shows that the effect of students' scientific curiosity levels on critical thinking occurs indirectly through scientific collaboration and that this indirect effect varies depending on the level of scientific inquiry. In this context, it can be said that students with high scientific inquiry skills are more effective at transforming their scientific curiosity into critical thinking.

When examined in Figure 1, the line representing indirect effects shows a significant increase as the level of scientific inquiry progresses from low to high. This situation reveals that, rather than a direct link between students' scientific curiosity and critical thinking skills, it is a mechanism operating through scientific collaboration that is effective. In other words, scientific collaboration both nurtures students' curiosity and supports their critical thinking, leading to a noticeable increase in their scientific inquiry levels. The difference between students with low levels of scientific inquiry and those with high levels of inquiry is particularly evident in the indirect effect. In contrast, the line representing the direct effect is almost horizontal, indicating that there is no significant change in the level of scientific inquiry at low, medium, and high levels.

Figure 2
Moderated Mediation Effect of Scientific Inquiry



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This implies that scientific curiosity and critical thinking alone are not sufficient to sufficiently stimulate the student's inquiring attitude, and that intermediaries such as social interaction (scientific collaboration) are needed to strengthen the association between them. In short, the graph reveals that scientific collaboration plays a critical role in developing students' scientific inquiry capacities and that the impact of this mediator is much stronger than direct effects. This finding emphasizes the importance of designing and encouraging collaborative scientific activities in learning environments.

Discussion

The qualitative findings of the study reveal that teachers' perceptions of scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry are consistent with student-centered learning approaches and have a multidimensional and pedagogically transformative structure. Teachers' statements reflect an approach that transforms students from passive recipients of information into active agents, encouraging skills such as self-regulation, independence, critical reasoning, and scientific productivity. These findings are highly consistent with the existing literature and theoretical approaches (Antink-Meyer et al., 2023; Chaparro-Banegas et al., 2024; Dehghanzadeh et al., 2024; Forman, 2020; Keengwe, 2022; Recker, 2021; Ribosa & Duran, 2022; Suwono et al., 2021; Willis & Willis, 2020). First, the concept of scientific curiosity was defined by teachers not only as a trigger for the learning process but also as the fundamental motivational source for deep learning, meaning construction, and scientific thinking. This definition aligns with the "motivation to discover" emphasized in Bruner's (1961) constructivist theory (Sweller, 2009). The student's questioning and attempt to make sense of the process through curiosity, rather than passively receiving information, recalls both Piaget's concept of cognitive disequilibrium and Dewey's emphasis on experience- and problem-based learning. Indeed, the findings in the study that curiosity directs students away from rote learning toward knowledge production and develops independent learning skills are consistent with Guthrie and Wigfield's (2000) theory of intrinsic motivation. However, an important critical point here is whether curiosity can be systematically supported in the pedagogical environment. The literature emphasizes that teaching strategies must be consciously structured for curiosity to be a sustainable learning engine (Judijanto et al., 2025; Karwal et al., 2023; Madison, 2023; Nicolopoulou et al., 2021; Whitworth, 2025). Although the teachers participating in the study were aware of this potential, there is limited data on what strategies they actually implemented. This suggests that, although teachers' perceptions are positive in terms of supporting students' curiosity, there may still be a gap in terms of translating this into pedagogical practice. On the other hand, findings on scientific collaboration show that interaction among students nourishes not only academic but also social-emotional development. In particular, exposure to different perspectives, empathy development, and collective production emphasize Vygotsky's (1978) social constructivism theory. This approach, which argues that learning is constructed within a social context, views collaboration not merely as a tool but as learning itself. The ways in which participating teachers interpret scientific collaboration are parallel to Johnson & Johnson's (1985) theory of collaborative learning. According to this theory, when students work toward common goals, both their academic achievement and social skills improve. However, the fact that teachers mostly define scientific collaboration in terms of values and attitudes gives the impression that they emphasize the cognitive dimension of collaboration relatively less. However, research and related literature (Abegglen et al., 2023; Chen et al., 2023; Forbes, 2022; Muchie et al., 2024; Pu & Barnard, 2025; Su et al., 2017) indicate that effective collaboration environments must also encompass cognitive processes such as planned task distribution, interaction, and individual responsibility. In this context, while it is positive that teachers' views focus on affective gains, there is a need to develop awareness of strategies that will reinforce the academic outcomes of collaboration. However, the concept of critical thinking has been defined by teachers in the context of students questioning knowledge, producing alternative solutions, and gaining mental independence. This approach aligns with Ennis' (1985) components of critical thinking, which include analysis, evaluation, inference, and decision-making skills. The participants' view of this skill as the basis of scientific progress also aligns with Paul and Elder's (2006) theoretical framework, which positions critical thinking as a way of life. However, the fact that teachers' statements largely focus on individual awareness and mental freedom indicates that the structural and cultural dimensions of critical thinking are not sufficiently addressed. In this context, teachers' tendency to view critical thinking more as an individual competence means that critical pedagogy overlaps with the understanding of critical thinking only to a limited extent (Book, 2024; Cottrell, 2023; Hanscomb, 2023; Kirk et al., 2023; McPhee & Cox, 2024; Paul & Elder, 2020). Finally, the concept of scientific inquiry has been defined in teachers' statements as a systematic form of learning that encompasses the processes of observation, hypothesis formation, testing, and drawing conclusions. This approach aligns with the fundamental principles of the scientific method (Anupam,

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2022; Bagdi et al., 2024; Bansal & Ramnarain, 2023; Cook & Wheeler, 2023; Ninos, 2023; Shearmur, 2020; Singh et al., 2023), it emphasizes the importance of constructivist learning environments that encourage students to take on the role of researchers in the learning process. Furthermore, these findings align with the four levels of learning in Schwab's (1962) "scientific inquiry" model. However, teachers' views that students acquire higher-order skills such as systematic thinking and tolerance for error in the scientific inquiry process contradict traditional approaches to error in education. It is debatable whether the right-wrong-centered assessment systems that are still dominant in the Turkish education system support such process-oriented approaches. Therefore, it can be said that teachers' intentions to support such skills may remain limited unless they are supported by systemic practices.

The quantitative findings of the study show that there are strong and meaningful connections between students' scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry skills. This reveals that learning processes are shaped not only by individual cognitive factors but also by social interaction and inquiry-based experiences. First, the strong associations between scientific curiosity and both scientific collaboration and critical thinking suggest that students' natural inclinations toward learning may have a transformative effect on their social and intellectual development. This finding is consistent with the relevant literature and previous research, which have shown similar patterns (Bjerknes et al., 2023; Dos Santos & Krause, 2017; Elder & Paul, 2020; Fasko & Fair, 2020; Liu, 2020; Meyer et al., 2024; Pu & Xu, 2023; Rousseau & van Gelder, 2024; Shahriary et al., 2020). Curiosity functions as an internal spark that initiates learning; however, this spark only transforms into sustainable learning when appropriate social and cognitive environments are provided. In this sense, social-cognitive interactions such as collaboration and questioning play a decisive role in the transformation of individual curiosity into critical thinking. The research results reveal that scientific collaboration serves as an important bridge in the process of developing students' critical thinking skills. It is observed that meaningful interactions between students not only enable the sharing of knowledge but also reconstruct thought structures. This finding aligns with Vygotsky's (1978) social constructivist approach, supporting the idea that learning develops through interaction in a social context. In particular, scientific group work contributes to students developing different perspectives, learning evidence-based thinking, and enhancing their ability to evaluate alternative viewpoints. This is similar to the relevant literature and research, which have emphasized the benefits of collaboration (Fan et al., 2023; Hou et al., 2020; Lee & Haupt, 2020; Nahar & Tayem, 2024). The role of scientific inquiry in the study is noteworthy in terms of students experiencing scientific thinking not only as a passive process of acquiring knowledge but also as an active process of research and problem solving. Inquiry-based learning environments encourage students to generate questions about topics they are curious about, develop hypotheses about these questions, and use strategies to test these hypotheses. In this context, the inquiry process becomes not only a learning method but also a mental habit that supports the student's cognitive development. A particularly noteworthy finding is that as students' level of scientific inquiry increases, the association between scientific curiosity and critical thinking becomes more pronounced. This situation shows that individual curiosity can only evolve into deep thinking and meaningful learning when the student has an inquiring attitude. In other words, as students develop scientific inquiry skills, they are able to express their curiosity in a more systematic and critical manner, which advances their scientific thinking skills to a higher level. In this context, the research results are consistent with the existing literature, which has highlighted similar relationships (Chatfield, 2022; Concannon et al., 2020; Dave, 2024; Gai et al., 2022; Kenett et al., 2023; Mahat & Kandel, 2023; Paavola & Shook, 2021; Pollarolo et al., 2022; Shellito, 2020; Wulff, 2022). However, Chin & Osborne (2008) have noted that students' active participation in scientific inquiry processes increases their depth of thinking, while Kuhn (1999) emphasizes the importance of peer interaction and discussion environments in the development of critical thinking. Similarly, Mercer & Littleton (2007) have demonstrated how collaborative learning transforms individual thinking skills. When evaluated together with these studies, the findings show that students' individual learning tendencies can only be transformed into higher-level skills when integrated with social and cognitive support. From a critical perspective, this research clearly demonstrates that students' learning processes are multidimensional. It is not enough for students to simply be curious; they need social environments where they can structure their curiosity, research-based activities, and a learning climate that is open to questioning. Otherwise, individual learning motivation remains limited, and lasting and deep learning does not occur. Therefore, learning environments should adopt an approach that focuses not only on individual success but also on collective productivity and the construction of shared knowledge.

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Conclusions and Implications

This study comprehensively examined the correlations between students' scientific curiosity, scientific collaboration, critical thinking, and scientific inquiry skills in a multidimensional manner using both quantitative and qualitative data, thereby revealing the individual and social components of contemporary learning approaches. The findings show that learning cannot be reduced to individual cognitive processes alone; it is a complex structure shaped by factors such as social interaction, affective participation, and the pedagogical environment. The transformation of students' scientific curiosity into sustainable learning is only possible with the existence of social, cognitive, and inquiry-based learning environments where this curiosity can be structured. Scientific collaboration not only enables the sharing of knowledge but also the collective restructuring of thought, which supports the development of critical thinking skills. In particular, inquiry-based learning processes have been observed to nurture students' scientific thinking habits and strengthen the association between scientific curiosity and critical thinking. Qualitative data reveal that teachers' pedagogical perceptions of these concepts align with a student-centered, discovery-based, and constructivist understanding; however, they also indicate that the impact of these positive trends may be limited if they are not translated into strategic planning at the implementation level. This situation highlights the need for teacher education programs to focus not only on theoretical knowledge but also on concrete pedagogical strategies for integrating this knowledge into classroom practices. Theoretically, the research findings are highly consistent with contemporary learning theories such as constructivist learning theory, social constructionism, and intrinsic motivation theory, providing a comprehensive theoretical framework that explains how individual curiosity interacts with social collaboration and inquiry processes in the development of scientific thinking. In this context, the emphasis on the need to support individual learning motivations with social learning contexts makes important contributions to the educational research literature. From an applied/practical perspective, this research highlights the critical role of learning environments that trigger students' curiosity and encourage collaboration in developing higher-order cognitive skills such as critical thinking and scientific inquiry in classroom applications. Educational programs should be enriched with interdisciplinary and inquiry-based activities that address these components in a holistic manner. It is recommended that in-service training programs be restructured and pedagogical leadership be strengthened so that teachers' awareness of these skills can be reflected in classroom practices. In addition, assessment processes should focus not only on outcomes but also on the process, allowing for freedom to make mistakes and encouraging a learning climate.

Recommendations

Research findings highlight the importance of educational policies and pedagogical approaches that support the development of students' scientific curiosity, collaboration, critical thinking, and scientific inquiry skills. In this context, teacher training programs must go beyond theoretical knowledge and include practical strategies that enable these skills to be effectively transferred to the classroom. It is important for teachers to gain practical skills in in-service training, for learning environments to be designed in a way that encourages curiosity and supports discovery, and for interdisciplinary, student-centered projects to be implemented. Assessment systems should focus on the process and provide meaningful feedback to students.

Limitations

This study has several limitations. First, the qualitative data are drawn from a small number of teachers, which may limit the generalizability of the findings, and their perspectives may not represent teachers in different sociocultural contexts. Additionally, the RMSEA value of the Scientific Curiosity Factor was .076, indicating a slightly suboptimal model fit. The quantitative data were cross-sectional, preventing the examination of longitudinal changes in interactions among scientific curiosity, collaboration, critical thinking, and inquiry. Moreover, application-level data were based on teacher self-reports, providing limited insight into actual classroom practices. Future studies should include student perspectives and observation-based methods to gain a more comprehensive understanding of students' cognitive and affective development.

Declaration of Interest

The authors declare no competing interest.

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PROFILING SCIENTIFIC INQUIRY SKILLS: EXPLORING RELATIONSHIPS WITH SCIENTIFIC COMPETENCY AND BACKGROUND FACTORS IN HIGH SCHOOL STUDENTS

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Chi-Jung Sui,
Chun-Yen Chang

Abstract. *Scientific inquiry skills are crucial for scientific literacy and cognitive development in the 21st century. Prior research has identified key inquiry skills—data analytics (DA), control of variables (COV), and scientific reasoning (SR)—but has not validated these skills through comprehensive assessments. The aim of this study was to validate and examine the relationship between students' inquiry skill profiles and their scientific competency. Through latent profile analysis (LPA), this study classified 667 Taiwanese high school students into three profiles: Sophisticated, Experimental, and Basic. The Sophisticated profile demonstrated strong proficiency in DA, COV, and SR, while the Experimental profile excelled in DA with moderate COV and SR skills. The Basic profile revealed deficiencies across all inquiry skills. ANOVA results indicated significant differences in scientific competency across profiles, with Sophisticated students outperforming others. Additionally, students' majors significantly influenced profile distribution, with natural science majors more likely to be classified as Sophisticated or Experimental. No significant relationship was identified between inquiry profiles and gender, parental education, or financial status. These findings highlight the importance of reasoning skills in scientific competency and suggest the need for tailored educational interventions to enhance students' inquiry abilities. The study provides empirical evidence for the applicability of inquiry skill profiles in diverse educational contexts.*

Keywords: *latent profile analysis, scientific competency, inquiry skills, reasoning skills*

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Introduction

Inquiry skills are essential components of scientific literacy and fundamental to 21st-century cognitive competencies. These skills have garnered increasing attention in response to evolving science education standards (Abd-El-Khalick et al., 2004; Gagné, 1963; National Research Council, 2000; Zhou et al., 2016). Scientific inquiry fosters critical thinking and problem-solving, enabling students to engage in systematic exploration. Lipman (2003) has highlighted the importance of cultivating an integrated thinking approach within scientific inquiry practices. Prior research has consistently underscored key dimensions of inquiry skills, including data analytics (DA)—the ability to analyze and interpret data to derive meaningful insights, control of variables (COV)—the capacity to systematically manipulate and isolate variables to establish causal relationships, and scientific reasoning (SR)—which encompasses logical analysis, hypothesis evaluation, and evidence-based argumentation (Bao et al., 2009; Chen & Klahr, 1999; Chen et al., 2023; Kuhn & Pease, 2008; Omarchevska et al., 2022; Sui et al., 2023; Wu & Hsieh, 2007).

Beyond cognitive skills, inquiry skills also involve attitudinal dimensions that influence students' engagement and problem-solving approaches (Gibson & Chase, 2002; Windschitl, 2003). Sui et al. (2024) developed a scientific inquiry skill profile model using latent profile analysis (LPA) to classify students based on their likelihood of exhibiting distinct inquiry skill patterns (Spurk et al., 2020). Their study examined learners' performance in an animation-based activity (ABA) designed to assess DA, COV, and SR. However, while this profiling approach has identified distinct inquiry skill patterns, it did not validate these profiles through standardized assessments of scientific competency. As a result, it remains unclear whether students categorized under different profiles possess corresponding levels of domain-specific scientific knowledge. Investigating this relationship is crucial for understanding how inquiry skills translate into scientific competency in practice.

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To address this gap, the present study integrates a formal assessment of students' scientific competencies and examines their relationship with the inquiry skill profiles identified by Sui et al. (2024). Specifically, this study employs replication research, which plays a critical role in educational research by confirming previous findings (Makel et al., 2019), identifying moderating variables (Perry et al., 2022), and expanding theoretical models to new contexts (Hedges, 2018; Morrison, 2022). This study utilizes assessment items from Inquiry in Scientific Thinking, Analytics, and Reasoning (iSTAR) alongside science examination questions from Taiwan's national secondary-level assessments. The iSTAR framework provides a structured approach to evaluating scientific reasoning across core inquiry dimensions, including DA, COV, and SR (Bao et al., 2022). By incorporating these assessments, this study sought to validate the predictive utility of inquiry skill profiles in determining students' scientific competency.

Scientific Inquiry

The National Science Education Standards (NSES) defines scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on evidence derived from their work" (National Research Council, 1996, p. 23). This definition aligns with various academic perspectives, which conceptualize scientific inquiry as a process involving key steps such as question formulation, hypothesis development, experimentation, planning, prediction, model utilization, data collection and analysis, result interpretation, and knowledge dissemination (Bell et al., 2010; Minner et al., 2010).

In contrast to traditional views that consider scientific competence as a sum of individual skills, contemporary global assessments—such as the Programme for International Student Assessment (PISA)—underscore a more integrative approach. PISA emphasizes that students' engagement in science learning and their ability to address real-world scientific problems require the dynamic application of multiple interrelated skills (OECD, 2017). This shift highlights the importance of understanding how students apply scientific inquiry skills rather than simply measuring isolated competencies.

Prior research (Bao & Koenig, 2019; Bao et al., 2022) has identified three core scientific inquiry skills essential for students' active participation in the learning process:

1. Data analytics (DA) – identifying trends and patterns in data to extract meaningful insights.
2. Control of variables (COV) – designing and conducting experiments by systematically manipulating variables to establish causality.
3. Scientific reasoning (SR) – linking evidence to logical conclusions through structured reasoning processes.

These skills form the foundation of scientific inquiry, equipping students with the ability to interpret data, design controlled experiments, and develop causal explanations, all of which are crucial for engaging meaningfully with scientific problems. DA refers to the ability to recognize patterns and trends within data, enabling data-driven decision-making (Gandomi & Haider, 2015). Developing DA skills allows students to analyze collected data systematically, interpret it as evidence, and draw informed conclusions about causal relationships (Bao et al., 2022).

COV is a critical experimental strategy that enables students to establish causal inferences by isolating and systematically manipulating a single variable at a time (Strand-Cary & Klahr, 2008; Tschirgi, 1980). Mastery of COV has been identified as a strong predictor of scientific competence (Bryant et al., 2015) and serves as a fundamental principle in scientific reasoning (Kuhn, 2007). Engaging in experimental setup and variable specification fosters learners' ability to conduct rigorous scientific investigations and draw valid conclusions. SR is the cognitive process of deriving conclusions from empirical evidence and logical inference (Lohman & Lakin, 2011; Zimmerman, 2007). Shaw (1996) defined reasoning as the act of linking facts and evidence to support logical conclusions. SR is integral to the scientific learning process, as it underpins hypothesis testing, systematic variable manipulation, and the evaluation of experimental outcomes (Bao et al., 2009). Through scientific reasoning, students refine their inquiry abilities by iteratively developing, testing, and revising knowledge based on observed evidence.

Latent Profile Analysis

LPA is a categorical latent variable modeling technique designed to identify latent subpopulations within a broader demographic based on shared characteristics (Collins & Lanza, 2009; Wang & Hanges, 2011). By employing probabilistic classification, LPA assigns individuals to distinct subgroups, each characterized by unique configurations of personal and situational variables. This person-centered methodology identifies typologies of individuals by analyzing patterns in observed indicators (Spurk et al., 2020), offering a structured approach to understanding

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heterogeneity within a population. The resulting categorical latent variable models provide an effective means of capturing underlying subgroup structures, enhancing the interpretation of population diversity (Howard & Hoffman, 2018).

A key consideration in applying LPA is the determination of an appropriate sample size to ensure reliable profile identification. Simulation-based evidence indicates that a sample size of around 500 is ideal for reliable classification (Nylund et al., 2007). Additionally, selecting the most suitable profile solution requires evaluating various goodness-of-fit indices, including the Akaike information criterion (AIC), Bayesian information criterion (BIC), sample-size adjusted BIC (SABIC), bootstrapped likelihood ratio test (BLRT), and entropy (Spurk et al., 2020). Lower AIC, BIC, and SABIC values indicate a more parsimonious and better-fitting model (Weller et al., 2020). Entropy, ranging from 0 to 1, measures classification accuracy, with values above 0.8 considered satisfactory (Celeux & Soromenho, 1996; Clark, 2009). Furthermore, a significant p-value for the Lo-Mendell-Rubin likelihood ratio test (LMR-LRT) and BLRT suggests that a model with a greater number of profiles provides a superior fit compared to a more parsimonious solution.

While statistical criteria play a vital role in determining model fit, past research emphasizes the importance of integrating theoretical and substantive considerations in profile selection (Gabriel et al., 2015; Hirschi & Valero, 2017; Vermunt, 2002; Woo et al., 2018). A well-constructed LPA model should not only demonstrate strong statistical validity but also align with theoretical frameworks and empirical insights to ensure meaningful interpretation.

Recent years have witnessed a surge in LPA applications within the field of science education, reflecting its growing recognition as a valuable methodological tool. An analysis of the Scopus database (2016–2023) reveals an increasing number of studies utilizing LPA, with 16 articles published in leading journals such as the International Journal of Science Education, Science Education, Journal of Research in Science Teaching, Research in Science Education, and International Journal of Science and Mathematics Education.

Several studies illustrate the diverse applications of LPA in science education. For instance, Sui et al. (2024) employed LPA to classify 11th-grade Chinese students' inquiry skill profiles, while Galano et al. (2024) utilized LPA to identify attitudinal profiles among Italian students in grades 9–13. Additionally, Snodgrass et al. (2020) explored the mathematics and science beliefs of underrepresented student populations, leveraging LPA to examine their attitudes and perceptions. This trend highlights the increasing adoption of LPA for investigating individual differences in science learning and engagement.

The selection of LPA in this study is driven by its alignment with a person-centered approach (Bergman & Trost, 2006; Collins & Lanza, 2009), which facilitates the identification of heterogeneous learning profiles within a dataset. As a form of mixture modeling, LPA assesses the existence of multiple latent profiles by evaluating the fit of competing models (Goodman, 2002; Bowers et al., 2013). This technique is particularly advantageous for distinguishing whether students exhibit a singular pattern of inquiry skills or a mixture of distinct profiles within the target population.

By employing LPA, this study sought to explore how many distinct profiles of inquiry skills best represent Taiwanese students and examine how these profiles relate to demographic characteristics and scientific competency. This study aimed to extend existing research on inquiry-based learning by providing a refined classification system that links students' inquiry abilities with their broader academic performance.

This study contributes to the field in two significant ways. First, it replicates and validates the inquiry skill profile model, reinforcing its generalizability across diverse educational contexts. Ensuring the stability of these profiles strengthens their applicability in future research and practice. Second, this study builds upon previous work by examining how different inquiry skill profiles are associated with scientific competency. By providing empirical evidence that distinct profiles predict variations in scientific performance, this study enhanced the model's utility as both a descriptive and predictive tool. In summary, the study addressed the following research questions:

4. To what extent can the inquiry skill profiles be replicated and validated?
5. How do students' scientific competencies, as measured by iSTAR and Taiwan's national science examinations, differ across the identified inquiry skill profiles?
6. To what extent do demographic factors moderate the relationship between inquiry skill profiles and scientific competency?

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Research Methodology

General Background

This study employed a quantitative, cross-sectional research design grounded in a person-centered analytical approach. The research aimed to validate and replicate high school students' scientific inquiry skill profiles and examine their relationship with scientific competency and demographic characteristics. Data collection occurred over two academic years (2022–2023) in a public high school located in central Taiwan. The school was purposively selected due to the representative nature of its students' academic performance in national assessments. The study utilized LPA to identify distinct subgroups of learners based on their scientific inquiry skills. The use of LPA reflects a commitment to person-centered methodologies that capture heterogeneity in learners' cognitive profiles, as opposed to traditional variable-centered approaches. To assess students' inquiry and scientific competencies, the study integrated both performance-based assessments and standardized test items from the iSTAR and CAP assessments. The scope of the research included investigating the distribution of inquiry skill profiles, their predictive validity for scientific competency, and the influence of demographic factors such as gender, academic major, family financial background, and parental education.

Sample Selection

This study examined high school students' scientific inquiry abilities, with the goal of assessing the robustness and transferability of inquiry skill profile classifications. Previous studies utilizing LPA have indicated that a minimum sample size of around 500 participants is necessary to achieve adequate model stability and estimation accuracy (Morgan, 2015). In this study, this senior high school was selected due to its representative student academic performance, as prior research has demonstrated that its students' General Scholastic Ability Test (GSAT) scores closely align with the national probability distribution (Chang & Cheng, 2008; Lin & Chang, 2017). The participants, specializing in both natural and social sciences, were purposively sampled from a centrally located school in Taiwan. Data were collected from 667 high school students (aged 15–16 years) over two consecutive years. Before data collection, informed consent was obtained from the school administration and participating students. Background information—including gender, academic major, parental education level, and family financial status—was gathered to explore potential influences on scientific inquiry skill profiles and their relationship with scientific competency.

Instrument and Procedures

Animation-based activities

The ABA integrates multiple representations, dynamic visualizations, seamless 2D-to-3D transitions, and cognitive load reduction techniques to enhance students' engagement and comprehension of scientific inquiry (Papadakis, 2022; Papadakis, Kiv, et al., 2023; Papadakis, Kravtsov, et al., 2023; Wu & Shah, 2004). This rigorously validated inquiry-based learning activity (Sui et al., 2024) was implemented in Taiwanese high schools, with content carefully translated from Simplified Chinese to Traditional Chinese to ensure accessibility and linguistic accuracy.

Developed on the CCR platform (https://ccr.tw), ABA consists of a structured sequence of learning components, including a preface, two animation experiments (AE1 and AE2), and five assessment tasks. The activity begins with an introductory preface that contextualizes the topic by discussing rising atmospheric methane levels and emphasizing methane's significantly greater heat absorption capacity compared to carbon dioxide.

The first animated experiment (AE1) presents a comparative setup featuring three bottles: Bottle A contains air and $H_2O_{(l)}$, Bottle B contains air, $H_2O_{(l)}$, and CO_2, and Bottle C contains air, $H_2O_{(l)}$, and CH_4. Following this visualization, students complete Task 1, a multiple-choice question designed to assess their DA skills by interpreting the experimental setup.

Building upon the first experiment, AE2 extends the scientific investigation by incorporating an animated procedure that simulates exposure to UV light. This simulation introduces an essential concept in atmospheric chemistry by making water vapor and hydroxyl radicals visible. After engaging with AE2, students proceed to three additional assessment tasks. Tasks 2 and 3 consist of multiple-choice questions evaluating students' DA skills. Task 4, an open-ended response item, assesses their SR abilities, requiring them to construct logical explanations based

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on the presented evidence. Task 5, another open-ended task, measures students' COV skills, challenging them to design or evaluate experimental conditions.

The illustrations of ABA are provided below (Figures 1, 2, 3, 4, 5, 6, and 7). The original task descriptions were presented in Traditional Chinese for student activities, and the accompanying figures include English translations for clarity and accessibility.

Figure 1
The preface of the ABA

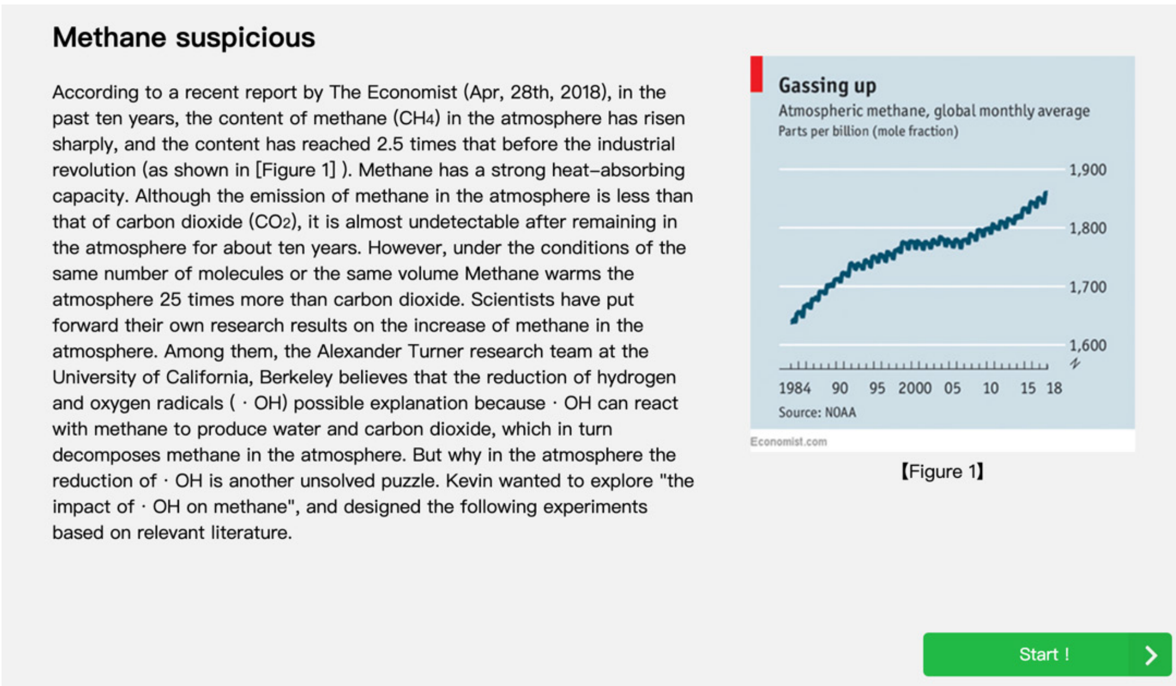
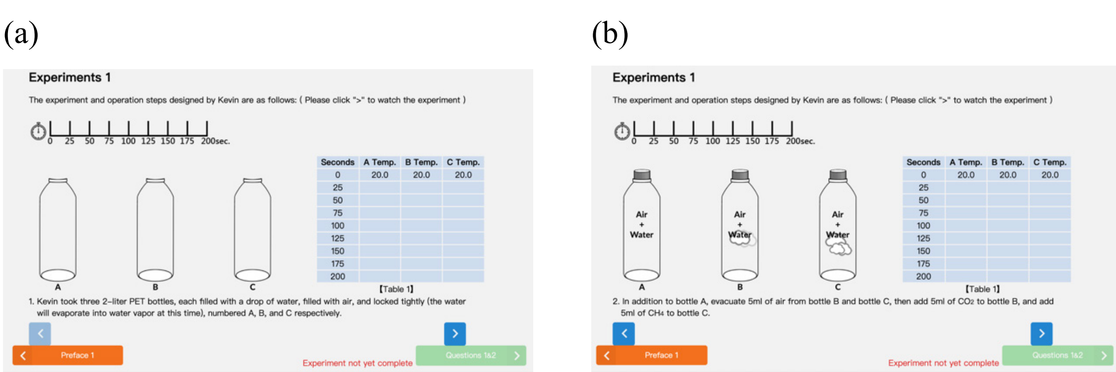


Figure 2
Animation experiment 1 (AE1)



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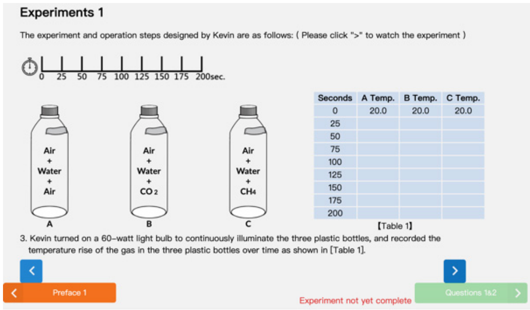
(c)



(d)

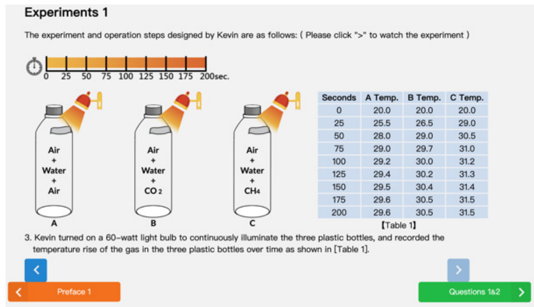
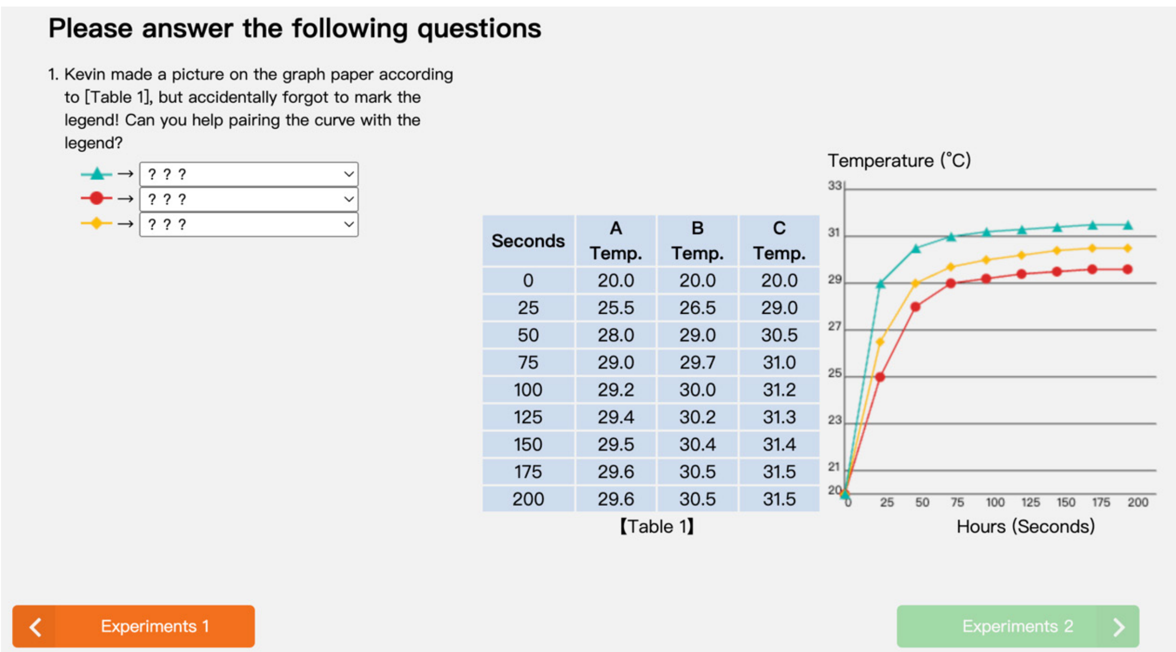


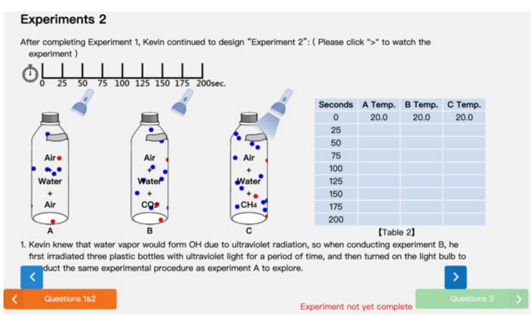
Figure 3
Task 1



Seconds	A Temp.	B Temp.	C Temp.
0	20.0	20.0	20.0
25	25.5	26.5	29.0
50	28.0	29.0	30.5
75	29.0	29.7	31.0
100	29.2	30.0	31.2
125	29.4	30.2	31.3
150	29.5	30.4	31.4
175	29.6	30.5	31.5
200	29.6	30.5	31.5

Figure 4
Animation experiment 2 (AE2)

(a)



(b)

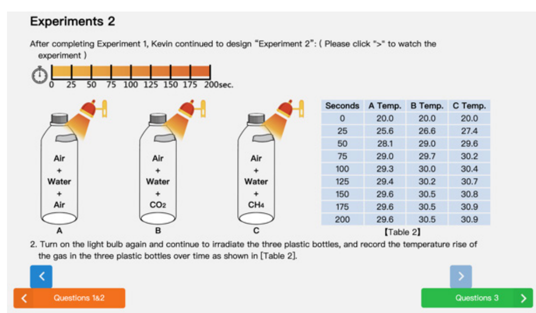


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Figure 5
Task 2

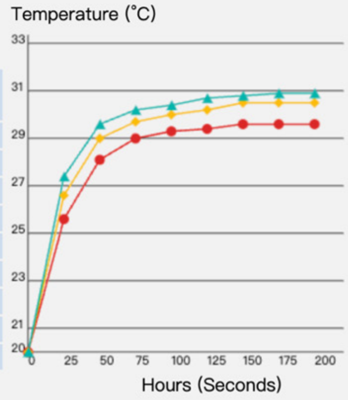
Please answer the following questions

3. The careless Kevin also confused the legend of the graphing results of Experiment 2! Please help him pair the curves and legends again.

→ ? ? ?
→ ? ? ?
→ ? ? ?

Seconds	A Temp.	B Temp.	C Temp.
0	20.0	20.0	20.0
25	25.6	26.6	27.4
50	28.1	29.0	29.6
75	29.0	29.7	30.2
100	29.3	30.0	30.4
125	29.4	30.2	30.7
150	29.6	30.5	30.8
175	29.6	30.5	30.9
200	29.6	30.5	30.9

【Table 2】



Experiments 2

Question 3 have not yet been answered

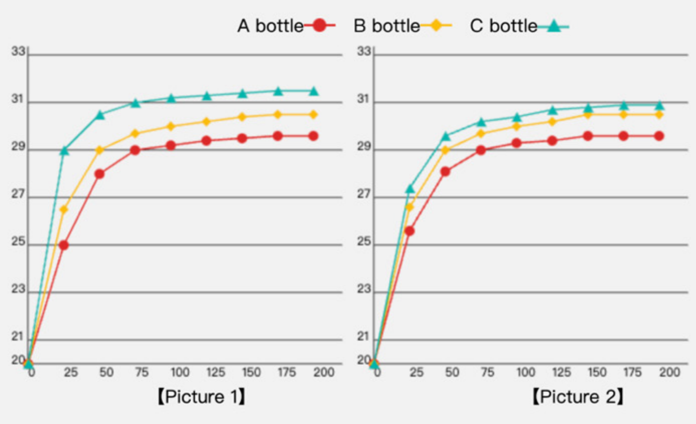
Questions 4

Figure 6
Task 3

Please answer the following questions.

4. Please compare the [Picture 1] and [Picture 2]. What are the changes in curves A, B, and C? (Multiple choice, please choose 2 items)

- ☐ A curve is almost unchanged.
- ☐ Significant changes in B curve
- ☐ C curve is almost unchanged
- ☐ C curve becomes closer to the B curve
- ☐ Superposition of C curve and B curve



Questions 3

Question 4 have not yet been answered

Questions 5&6

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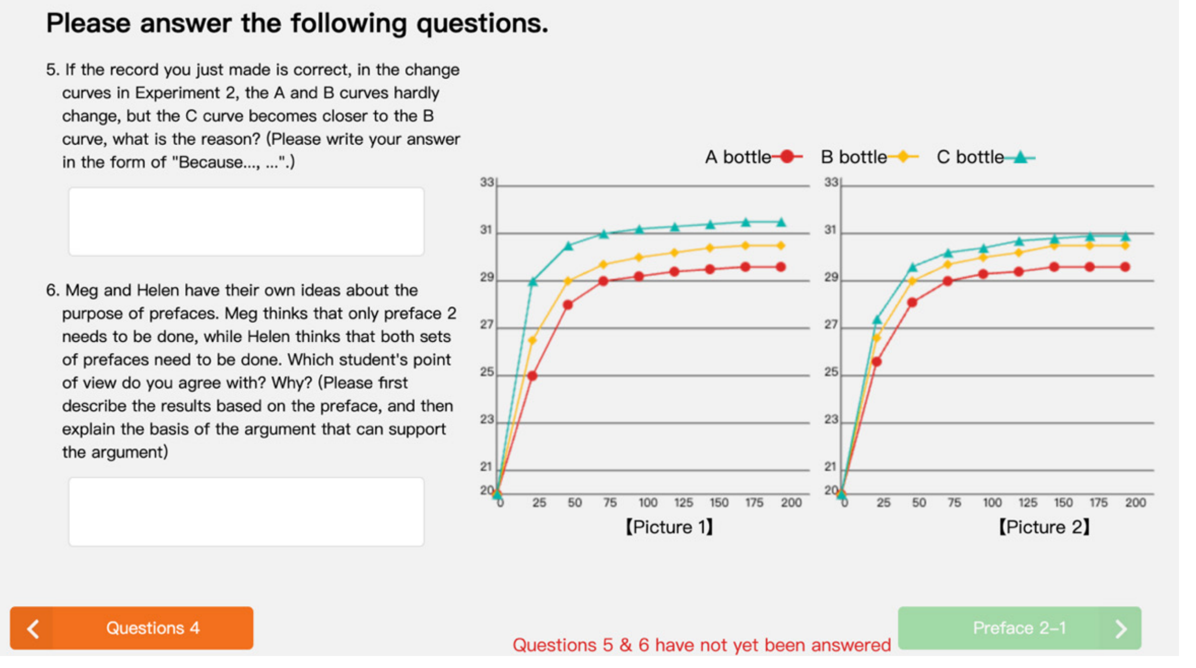
Figure 7
Task 4 and Task 5



Scientific Competency Test

The Scientific Competency Test was employed to assess the relationship between students' inquiry skill profiles and their science achievement. This assessment consisted of 12 multiple-choice questions from the Taiwan Comprehensive Assessment Program (CAP) and 18 multiple-choice questions from the iSTAR assessment.

The CAP is a standardized science examination used for high school and vocational school admissions in Taiwan. Since 2012, the Taiwanese government has increasingly aligned CAP with the Programme for International Student Assessment (PISA), reflecting the growing influence of PISA rankings on educational policy and public perception (Yang & Lin, 2015). This integration has reinforced CAP's emphasis on scientific inquiry and problem-solving skills, making it a relevant measure for assessing students' science competency in line with international benchmarks.

The iSTAR assessment, developed by Bao et al. (2022), is a robust tool for evaluating scientific literacy, particularly within inquiry-based learning contexts. Over the past decade, iSTAR has undergone extensive qualitative and quantitative validation, ensuring its alignment with established science education frameworks such as PISA and TIMSS. The test assesses higher-order cognitive skills, including COV, DA, and causal decision-making, mirroring PISA's focus on explaining phenomena and designing investigations and TIMSS's emphasis on Knowing, Applying, and Reasoning (Mullis & Martin, 2013; OECD, 2017).

Unlike traditional assessments such as the Lawson Classroom Test of Scientific Reasoning (LCTSR), which have limitations in differentiation and scalability, iSTAR provides a more precise and adaptable evaluation of scientific reasoning. While originally designed for college entry and higher education assessments, its inquiry-based structure makes it well-suited for tracking the development of scientific reasoning from middle school onward. The validity and reliability of iSTAR have been rigorously tested using classical statistical methods and Rasch analysis, confirming its effectiveness in measuring scientific reasoning skills. Additionally, science education experts have reviewed and validated the assessment items to ensure construct validity, reliability, and relevance to the targeted competencies.

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Procedures

The study was conducted during regular school hours and consisted of two phases. First, students completed the Scientific Competency Test, designed to assess their understanding of key scientific concepts and their ability to apply scientific reasoning skills. Following this, students participated in an ABA, an inquiry-driven learning module that included multiple animated experiments and assessment tasks to evaluate their inquiry skills in an interactive context.

Data Analysis

Coding Approaches

Tasks 1, 2, and 3 assessed DA skills, with each task awarding two points for correctly matching all labels. To enhance scoring efficiency, Tasks 1 and 2, which focused on recognizing covariation in data, were averaged to provide a composite score. Task 3, a multiple-choice question, evaluated students' ability to distinguish between the charts in the previous tasks by including two correct options, requiring a more nuanced understanding of data representation.

Tasks 4 and 5, designed based on established coding criteria and prior research by Sui et al. (2024), examined distinct aspects of scientific inquiry skills. Task 4 assessed mechanistic causal reasoning, requiring students to explain interactions among key variables such as UV light, water, CO_2, methane, and hydroxyl radicals. A comprehensive response is needed to logically describe how water vapor reacts with UV light to form hydroxyl radicals, which subsequently interact with methane to produce CO_2. This process results in the gas composition in Bottle C resembling that of Bottle B, with the reaction nearing completion but not fully occurring. As a result, the curve for Bottle C approaches but does not exactly match that of Bottle B.

Task 5 aligned with the study's research objective by prompting students to compare the effect of hydroxyl radicals on methane. Participants analyzed two experimental setups:

1. Experiment 1 served as the control group, featuring a 60-watt light bulb with no hydroxyl radicals.
2. Experiment 2 represented the experimental condition, incorporating UV light and hydroxyl radicals.

This task required students to identify data-covariation relationships, determine necessary experimental conditions, and specify the corresponding independent variables to establish causality. To ensure scoring reliability, the first author evaluated all responses, ensuring consistency and accuracy in grading. Additionally, two independent authors double-checked all assessments, reinforcing the validity of the scoring process.

Analytical Strategies

This study used the tidyLPA package in R (version 4.1.0; Rosenberg et al., 2019) to do LPA. Models were estimated with increasing numbers of latent groups (1 to 10), following the equal variance and zero covariance model, as alternative specifications failed to converge. The analysis produced categorical latent variables, representing students' scientific inquiry skill profiles within the dataset ($n = 667$). To validate the final class solution, the dataset was randomly partitioned into two halves (Kampa et al., 2016). LPA was then re-executed on both subsets to ensure that the derived profiles remained consistent with the original model. This step was critical for assessing the stability and replicability of the identified profiles.

To identify the associations between students' inquiry skill profiles and their science competency, χ^2 tests and cross-tabulation analyses were employed. A threshold of $p < .05$ was determined for statistical significance (Agresti, 2012; Li et al., 2023). For significant associations, additional post-hoc tests were conducted using the Bonferroni correction and standardized Pearson residuals. Absolute residual values exceeding 1.96 were interpreted as indicating a significant difference at the .05 significance level.

Research Results

Students' DA skills were assessed through three tasks, each scored on a 0 to 2 scale. Table 1 presents the descriptive statistics for each task, including minimum and maximum scores, mean values, and standard deviations. On average, students scored 4.84 out of a maximum of 6 ($SD = 1.79$) across all three tasks, indicating a moderate level of proficiency in data interpretation and pattern recognition.

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Students' SR skills were evaluated through Task 4, which assessed four dimensions of cause-and-effect analysis. The task required students to examine the relationships among three distinct causes (C1, C2, C3) and a single effect (E1), emphasizing the interconnected nature of causal mechanisms. Each dimension was scored on a 0 to 1 scale. Table 2 provides descriptive statistics, including minimum and maximum scores, mean values, and standard deviations. Overall, students obtained an average score of 0.88 out of a maximum of 4 ($SD = 1.11$), suggesting difficulties in articulating mechanistic causal explanations.

Students' COV skills were assessed using Task 5, which measured two key dimensions: identifying the comparative group structure within the experimental design (CP) and recognizing the independent variable (IV). Each dimension was evaluated on a 0 to 1 scale. Table 3 summarizes the descriptive statistics, including minimum and maximum scores, mean values, and standard deviations. The average student score was 0.63 out of a maximum of 2 ($SD = 0.70$), indicating that students faced challenges in experimental design and variable control.

Table 1
Description of Students' DA

Task	Min	Max	*M*	*SD*
Task 1	0	2	1.51	0.86
Task 2	0	2	1.54	0.84
Task 3	0	2	1.79	0.48

Table 2
Description of Students' SR

Task		Min	Max	*M*	*SD*
Task 4	C1	0	1	0.18	0.39
	C2	0	1	0.18	0.39
	C3	0	1	0.10	0.29
	E1	0	1	0.43	0.50

Table 3
Description of Students' COV

Task		Min	Max	*M*	*SD*
Task 5	CP	0	1	0.40	0.49
	IV	0	1	0.23	0.42

Pearson correlation coefficients were computed to explore the correlation among students' performance in DA, SR, and COV skills. Table 4 presents significant positive correlations among all three inquiry skills, indicating a strong interconnection between them. There was a moderate positive correlation between DA performance and SR skills ($r = .301$, $p < .01$) as well as DA performance and COV skills ($r = .249$, $p < .01$). Additionally, a strong positive correlation was observed between SR skills and COV skills ($r = .459$, $p < .01$), suggesting that students with stronger scientific reasoning abilities tend to demonstrate better control of variables in experimental design. These findings highlight the interdependence of inquiry skills, suggesting that students who perform well in one area are likely to excel in others. The results further emphasize the importance of adopting a holistic approach to fostering inquiry skills, as interventions targeting one domain may yield broader improvements across multiple aspects of scientific inquiry.

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Table 4
The Correlations Among Students' Performance

Inquiry skills	DA	SR	COV
DA	1		
SR	.301**	1	
COV	.249**	.459**	1

Identification of inquiry skill profiles

LPA was performed using z-transformed averages of DA, COV, and SR. Models with different numbers of groups, ranging from one to eight, were evaluated based on various fit indices, while attempts to estimate more than nine groups failed to converge. To identify the optimal model, we examined several fit indices, including AIC, BIC, SABIC, entropy, and BLRT. Among these, the three-group model was the best fit, as it had the lowest AIC, BIC, and SABIC values (Weller et al., 2020). Additionally, the entropy and BLRT *p*-value were considered to further validate model selection. High entropy values for the two-group and three-group models suggested good separation between the groups (Celeux & Soromenho, 1996). Moreover, the BLRT *p*-value was below zero point zero for both models, indicating significantly better model fit compared to alternative solutions (Table 5). Overall, the three-profile solution was determined to be the best fit, as it demonstrated the lowest AIC, BIC, and SABIC values, along with strong entropy and BLRT p-values, confirming its superior fit over other models.

Table 5
Comparison of the Fit Models with Different Group Numbers

Indicators	1 group	2 group	3 group	4 group	5 group	6 group	7 group	8 group
Log-likelihood	-2828.8	-2594.1	-2435.4	-2434.9	-2411.4	-2080.0	-2418.7	-1904.1
AIC	5669.7	5208.2	4898.8	4905.8	4866.8	4212.0	4897.3	3876.3
BIC	5696.7	5253.3	4961.9	4986.9	4965.9	4329.0	5032.4	4029.4
SABIC	5677.6	5221.5	4917.4	4929.7	4896.0	4246.5	4937.2	3921.4
Entropy	1.00	.98	.93	.81	.83	.86	.66	.72
BLRT (p)	NA	.0099	.0099	.6931	.0099	.0099	.7525	.0099
Smallest group frequency	1.00	0.23	0.20	0.03	0.03	0	0	0

Based on the outcomes of the LPA, we characterized three distinct profiles, labeled as "Experimental," "Sophisticated," and "Basic." The Experimental profile (57.0%) comprised the largest number of students. The Sophisticated profile and Basic profile accounted for 19.9% and 23.1%, respectively. Figure 8 highlights the distinguishable nature of these profiles based on their inquiry skills. The Sophisticated profile demonstrated strong proficiency across SR, DA, and COV skills. The Experimental profile excelled primarily in DA, with moderate proficiency in COV and SR skills. Conversely, the Basic profile exhibited standardized mean scores below average across all three skills, indicating deficiencies in their performance.

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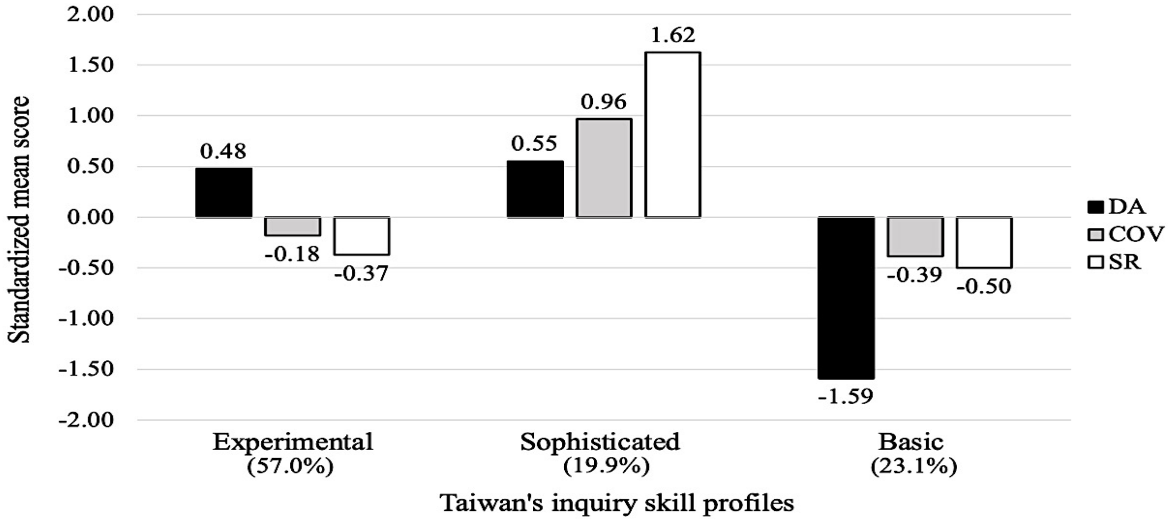
Figure 8
Taiwanese High School Students' Inquiry Skill Profiles



The Association Between Inquiry Profiles and Scientific Competency

One-way ANOVA was conducted to examine variations in scientific competency achievement among different profiles of students. Additionally, a $\chi 2$ test and cross-table analysis were utilized to evaluate the presence of significant associations between students' background factors, such as gender, major, parents' education level, and family financial situation. A descriptive analysis of the scientific competency scores for each profile is summarized in Table 6. The results demonstrate distinct performance levels across the profiles. The Sophisticated profile exhibited the highest average score (M = 18.44, SD = 4.91), demonstrating their advanced level of scientific competency. The Experimental profile ranked second with a moderately high average score (M = 16.06, SD = 5.59), while the Basic profile had the lowest average score (M = 13.23, SD = 6.55), indicating the greatest need for development.

Table 6
Description of Scientific Competency Test Scores of Different Profiles

Profile	*n*	*M*	*SD*	*Min*	*Max*
Experimental	380	16.06	5.59	0	30
Sophisticated	133	18.44	4.91	0	30
Basic	154	13.23	6.55	0	30

The one-way ANOVA analysis indicates significant differences in scientific competency test scores among different profiles, with a moderate effect size (F (2, 664) = 30.20, p < .001, partial η^2 = .083), as shown in Table 7. These results suggest that students categorized as 'Experimental,' 'Sophisticated,' and 'Basic' performed differently on the scientific competency test. Post hoc Bonferroni tests further revealed statistically significant differences in test scores (p < .001), with moderate and large effect sizes. Specifically, the Bonferroni tests identified significant mean differences between each pair of profiles. In summary, students classified as the Sophisticated profile demonstrated higher scientific competency than both the Experimental profile and the Basic profile, while the Experimental profile performed better than the Basic.

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Table 7

The Result of Post Hoc Bonferroni Tests of Different Profiles

Comparison		*M* difference	*SE*	*p*	*d*
Condition	Condition				
Sophisticated	- Experimental	2.378	0.575	< .001	.436
	- Basic	5.209	0.675	< .001	.895
Experimental	- Basic	2.831	0.545	< .001	.478

Table 8 presents the results of chi-square tests examining the association between students' background factors and their scientific inquiry skill profiles. The analysis shows no significant differences in the distribution of students' gender ($\chi^2 = 1.122$, $p = .571$), parents' education level ($\chi^2 = 15.490$, $p = .345$), and family financial situation ($\chi^2 = 1.749$, $p = .417$). However, a significant difference was found in the distribution of students' majors ($\chi^2 = 23.078$, $p < .001$), indicating that students' majors significantly influence their scientific inquiry skill profiles.

Table 8

Chi-Square Tests of Students' Background Factor

Background factor	χ^2	*p*
Gender	1.122	.571
Major	23.078	< .001
Parents' education level	15.490	.345
Family financial situation	1.749	.417

The distribution of inquiry skill profiles varies significantly between students majoring in social and natural sciences. Among social science majors ($n = 187$), 50.3% (94 students) are classified as Experimental profile, 14.4% (27 students) as Sophisticated, and 35.3% (66 students) as Basic. In contrast, for natural science majors ($n = 440$), 60.0% (264 students) are Experimental, 22.0% (97 students) are Sophisticated, and 18.0% (79 students) are Basic. A Pearson chi-square residual analysis revealed notable differences between these groups (Agresti, 2019). Follow-up tests indicated that the proportion of Experimental profile and Sophisticated among natural science majors is significantly higher than among social science majors, with standardized residuals of 2.25 and 2.19, respectively. Conversely, the proportion of Basic is significantly lower for natural science majors compared to social science majors (standardized residual = -4.71). Interestingly, across both groups, the Experimental profile represents over half of the students, suggesting that many possess basic data analysis skills. However, the proportion of Sophisticated, who exhibit advanced inquiry and reasoning capabilities, remains relatively low in both majors.

Discussion

Inquiry Skill Profile Model

This study identified three distinct inquiry skill profiles among Taiwanese high school students, highlighting variations in their proficiency across SR, DA, and COV. These profiles provide empirical support for partially replicating student classifications based on inquiry abilities. From a statistical modeling perspective, selecting $n = 3$ as the optimal solution is supported by multiple factors. First, BIC and SABIC values show a notable decrease at $n = 3$, whereas further increasing the number of profiles results in only marginal improvements. Second, the BLRT ceases to be significant beyond $n = 3$, indicating that additional profiles do not contribute significantly to the model. Third, the three-profile solution ensures an adequate sample distribution, preventing the formation of excessively small classes that may compromise statistical power. Finally, the $n = 3$ model aligns with theoretical and practical interpretability, preventing excessive complexity that could hinder meaningful application.

From a theoretical perspective, this decision is grounded in the e data-covariation and mechanistic causal reasoning framework (Bao et al., 2022), which underscores the role of DA in identifying covariation patterns and validating

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evidence for mechanistic causal relationships. Within this three-profile model, the Sophisticated group demonstrates strong DA abilities alongside high levels of COV and SR. In contrast, the Basic group exhibits weaker DA skills, with the lowest average performance in COV and SR. Additionally, Nkwanyana et al. (2023) highlighted that some students struggle to translate data analysis into meaningful insights, aligning with the Experimental group, which demonstrates moderate DA proficiency but suboptimal performance in COV and SR. As a result, the three-profile solution is both statistically and theoretically well-supported, offering an optimal balance between model fit, sample distribution, and interpretability.

Although the three-profile model identified in this study—Sophisticated, Experimental, and Basic—differs from the four-profile model proposed in China (Sui et al., 2024), the core characteristics of these profiles remain highly consistent across both contexts. In both models, the Sophisticated profile exhibits high proficiency across all inquiry skills, while the Basic profile reflects notable deficiencies. The Experimental profile identified in Taiwan closely aligns with China's Experimental and Moderate profiles, suggesting similar distributions of inquiry skills despite minor differences in classification.

From a model simplicity perspective, the three-profile solution effectively captures essential variations in students' inquiry abilities while maintaining clarity and usability. This streamlined framework reinforces the robustness and generalizability of inquiry skill profiling, demonstrating its adaptability across different educational settings. By validating and extending the inquiry skill profile model, this study enhances our understanding of students' scientific competencies and provides valuable insights for designing targeted interventions to improve inquiry skills in science education.

Students' Scientific Competency and Background Factors

The findings indicate that students classified within the Sophisticated profile exhibit the highest levels of scientific competency, significantly outperforming those in the Experimental and Basic profiles. This supports the notion that reasoning abilities are central to scientific competency (Bao et al., 2022) and play a crucial role in science learning (Coletta & Phillips, 2005). Reasoning skills have consistently been identified as essential for problem-solving and scientific inquiry, with research linking these skills to higher academic achievement in science (Alshamali & Daher, 2016). Moreover, scientific reasoning functions both as a cognitive skill and as a domain of knowledge, contributing to scientific competency and improved educational outcomes (Pasigon, 2024; Zimmerman, 2007). The exceptional performance of students in the Sophisticated profile underscores the importance of advanced reasoning capabilities in interpreting, synthesizing, and applying scientific concepts, aligning with prior research emphasizing these skills as critical for science education. Conversely, the lower reasoning proficiency observed in students within the Experimental and Basic profiles is closely associated with their reduced scientific competency. Adey and Shayer (1993) highlighted that developing science process skills has a lasting impact on learning, further underscoring the critical role of reasoning in educational outcomes. These findings emphasize the necessity of targeted interventions to strengthen reasoning skills, particularly for students in lower-performing groups, as a strategy to enhance scientific understanding and improve academic performance.

The findings also suggest that curricular design should be sensitive to students' academic focus, given the significant association between students' majors and their inquiry skill profiles. Students majoring in social sciences, who were more frequently classified as Basic, may require additional support to enhance their inquiry skills and bridge the gap with their natural science peers. To address this disparity, curriculum elements could be tailored to align with their academic background, for example, by integrating scientific inquiry within social science contexts, making these skills more relevant and accessible. Research suggests that students are more likely to retain and apply knowledge when it is taught in contexts that are meaningful and engaging (Iran-Nejad et al., 1990).

Furthermore, research by Russell and French (2002) indicated that nonscience majors often hold negative attitudes toward science, but experiential learning strategies can effectively overcome these barriers. By incorporating hands-on, inquiry-driven learning approaches, educators can create more engaging and meaningful science education experiences, ultimately improving inquiry skills among social science students.

Moreover, students majoring in natural sciences were more likely to be categorized as Experimental or Sophisticated, whereas those in social sciences were predominantly classified as Basic. This suggests that scientific inquiry skills may play a critical role in influencing students' academic choices. Students with stronger inquiry skills or those more inclined toward higher-level inquiry processes may gravitate toward natural science tracks, whereas those with less-developed inquiry skills may prefer social sciences.

This finding raises important considerations for science education policy. If students' inquiry skills significantly influence their academic pathways, early interventions that develop these skills could expand students' access to

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science-related disciplines. For instance, targeted support for students in the Basic profile could help mitigate skill-related barriers that deter some students from pursuing natural sciences. Additionally, the low proportion of students classified as Sophisticated across both groups highlights the need for enhancing advanced reasoning abilities across disciplines. These skills are essential for scientific competency and interdisciplinary problem-solving, reinforcing the importance of strengthening higher-order thinking skills within the broader education system.

There was no significant association between students' inquiry skill profiles and background factors such as gender, parental education level, or family financial status. This lack of association suggests that scientific inquiry skills may be relatively independent of these socioeconomic variables, indirectly supporting the effectiveness of Taiwan's science education system in promoting equity. The consistent performance patterns across different inquiry skill profiles indicate that Taiwan's education system not only delivers quality science education but also ensures equitable learning opportunities for students from diverse backgrounds.

However, caution is warranted in interpreting these findings. Studies examining multi-level moderation or mediation effects, or conducting subgroup analyses, often require large-scale datasets—such as those used in international assessments like PISA or TIMSS—to accurately detect subtle differences. To better understand the nuanced and context-dependent effects of socioeconomic status on learning outcomes, future research should consider larger and more diverse samples (Tan, 2024).

The implications are profound for education, particularly in tailoring instructional strategies to meet the diverse needs of students. By recognizing the three distinct inquiry skill profiles—Basic, Experimental, and Sophisticated—educators can design targeted interventions that address the specific needs of each group, ultimately enhancing overall educational outcomes.

Students in the Basic profile, who frequently struggle with science learning, would benefit from instructional interventions focused on building foundational skills and enhancing engagement. Glynn et al. (2007) suggested that linking science concepts to career pathways for nonscience majors can increase both engagement and achievement. This approach could involve strategically integrating real-world applications and experiential learning to make scientific inquiry more accessible. By increasing students' interest and confidence in science, their DA skills may improve, leading to enhancements in COV and SR abilities.

On the other hand, research by Kuhn (2007) highlighted that reasoning processes can be applied across multiple domains. Students in the Experimental profile, who generally exhibit strong analytical skills but may require further development in scientific reasoning, could benefit from more advanced inquiry-based tasks. Kind and Osborne (2017) propose that scientific reasoning varies based on both content knowledge and epistemic understanding. For these students, interventions could include complex problem-solving tasks or higher-order thinking exercises, bridging the gap between their current skill set and the advanced reasoning abilities required for scientific competency.

Limitation

This study has certain limitations in its data collection process. Although data were gathered from 667 students, the sample was restricted to a single high school in central Taiwan. Despite this limitation, the resulting model closely aligns with prior research, suggesting that the sampling approach is valid and that the findings are reliable. However, students from other regions in Taiwan or different cultural and educational contexts may exhibit variations in their inquiry skill profiles. While the observed similarities between Taiwanese and Chinese high school students indicate a degree of universality in inquiry skill classifications, additional research is needed to examine the applicability of these profiles across diverse cultural and educational settings. Such investigations would provide further validation of the universality of scientific education principles and offer deeper insights into how inquiry skill development is influenced by contextual factors.

While this study did not identify significant relationships between students' inquiry skill profiles and background factors such as gender, parental education level, and family financial status, this absence of statistical significance should not be interpreted as definitive evidence of no effect. Instead, it may reflect methodological constraints, including sample size limitations and measurement sensitivity. Additionally, the background variables in this study were broadly categorized (e.g., binary classifications of parental education level and financial status), which may not fully capture subtle socio-economic disparities that influence inquiry skills.

Future research could adopt more granular socio-economic indicators to gain a deeper understanding of how socio-economic factors shape inquiry skill development. Potential avenues for investigation include access to scientific learning resources at home, parental involvement in science education, and school-level contextual factors. A more comprehensive examination of these variables could provide richer insights into the relationship between socio-

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economic background and scientific inquiry skills, ultimately informing policy decisions and instructional interventions aimed at bridging educational gaps.

Conclusions and Implications

Scientific inquiry skills are essential indicators of students' cognitive abilities and their readiness to engage in scientific reasoning. This study successfully replicated and validated the inquiry skill profile model from previous research, confirming its robustness across different educational settings. Through LPA, we identified three distinct inquiry skill profiles—Sophisticated, Experimental, and Basic—each characterized by varying levels of proficiency in DA, COV, and SR. These findings provide empirical evidence that students' inquiry skills are not uniformly distributed, but rather follow distinct patterns based on their competencies in scientific inquiry.

Furthermore, this study established a significant correlation between students' inquiry skill profiles and their scientific competency. Students classified under the Sophisticated profile demonstrated higher scientific competency, significantly outperforming those in the Experimental and Basic profiles. These results emphasize the critical role of advanced reasoning abilities in enhancing students' understanding and application of scientific concepts. Conversely, students in the Basic profile exhibited the lowest levels of scientific competency, underscoring the need for targeted interventions to improve their inquiry skills.

Notably, demographic factors such as gender, parental education level, and family financial status did not significantly impact students' inquiry skill profiles, reinforcing the effectiveness of Taiwan's science education system in providing equitable learning opportunities. However, academic majors exhibited a strong association with inquiry skill profiles, with natural science majors demonstrating higher inquiry skill proficiency than their social science counterparts. This finding suggests that scientific inquiry skills may influence students' academic choices and highlights the importance of science curricula that support students across different disciplines.

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Declaration of Generative AI and AI-assisted Technologies

During the preparation of this work, the authors used ChatGPT in order to help with some stylistic issues and translation. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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EFFECTIVENESS OF PERSPECTIVE-TAKING SUPPORT IN A VISUAL LEARNING TASK ON THE CAUSE OF SEASONAL CHANGES: AN EYE-TRACKING APPROACH

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Sungman Lim,
Seongun Kim

Abstract. *This study examined the effectiveness of incorporating a visual element to support perspective taking in learning about the cause of seasonal changes. Participants were 44 sixth-form pupils who studied materials consisting of illustrations and explanatory texts. In the experimental group, the illustrations included a figure of an observer standing on the Korean Peninsula during summer and winter, whilst the control group viewed the same illustrations without the observer. During the task, eye-tracking devices recorded gaze data, and conceptual understanding was assessed before and after learning. Results showed no significant difference in the proportion of gaze fixation on core areas of the illustrations. However, significant differences emerged in fixation transitions, fixation durations on text, gaze shifts between illustrations and text, and post-test scores of understanding. Eye-movement analyses indicated that the experimental group engaged in cyclic gaze transitions between conceptually related elements of text and illustration, whereas the control group primarily processed text before shifting attention unidirectionally to the illustrations. These findings suggest that perspective-taking elements in visual materials promote qualitatively different cognitive processing strategies and enhance conceptual understanding of astronomical phenomena such as seasonal changes.*

Keywords: *astronomy education, eye-tracking, perspective taking, seasonal change, spatial reasoning*

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Introduction

Among various astronomical concepts, the cause of seasonal changes is particularly difficult for students to understand. Previous studies have reported that many students hold alternative conceptions about this topic, the most prevalent being the idea that the Sun is farther from the Earth in winter than in summer (Atwood & Atwood, 1996; Plummer et al., 2014; Schoon, 1995; Türk et al., 2016; Türk & Kalkan, 2018; Gali, 2021). The scientific explanation for seasonal changes is based on a model in which the Earth orbits the Sun with a tilted rotational axis. Unfortunately, this model is often perceived as disconnected from students' everyday experiences and observations made from the Earth's surface, and students are rarely provided opportunities to link their observations to this model (Plummer & Maynard, 2014). Consequently, students tend to adopt easily accessible alternative conceptions based on their everyday knowledge and experiences. Even after teaching, some students revert to these alternative conceptions, indicating the difficulty of constructing a scientific understanding of the causes of seasons changes through learning (Gali, 2021).

Both the Korean national science curriculum (MOE, 2022) and the Next Generation Science Standards (NGSS Lead States, 2013) suggest a stepwise learning process for understanding seasonal changes. First, students observe the apparent motion of the Sun and the solar altitude from the perspective of an Earth-based observer. Next, they examine the correlation between solar altitude and temperature variations. Finally, students are expected to explain the underlying cause of the observed seasonal patterns. In particular, the final step is designed to use a space-based observer model to explain the seasonal variation in the Sun's meridian altitude, encouraging students to connect their Earth-based observations with spatial reasoning from an external, off-Earth perspective. This stage poses a significant challenge for students, as it requires them to mentally represent Earth's orbit over time and integrate it with the Sun's apparent motion (Testa et al., 2014).

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One of the primary challenges in this reasoning process is related to spatial ability (Plummer et al., 2014; Plummer & Maynard, 2014; Wai et al., 2009). Understanding celestial motion is inherently spatial, and previous studies have consistently reported that students with lower spatial abilities struggle with astronomy concepts (Black, 2005; Plummer et al., 2014; Wilhelm, 2009). Students often find it difficult to shift mentally from an Earth-based perspective and to integrate newly learned solar motion patterns with a space-based model (Gali, 2021; NRC, 2006). The spatial skill essential to this integration is known as perspective-taking ability, which refers to the cognitive capacity to infer what is visible or hidden from another's viewpoint, as well as others' internal states such as knowledge and preferences (Moll & Tomasello, 2006). For effective learning of the cause of seasonal changes, students must be able to visualize the Sun's meridian altitude from an Earth-based perspective while modelling from a space-based perspective (Plummer et al., 2014).

However, in practice, such integration through perspective-taking is often not achieved. Previous studies analysing student explanations or educational designs related to the causes of seasonal changes have indicated a predominant emphasis on the space-based perspective, with insufficient opportunities for students to integrate it with the Earth-based perspective (Hansen et al., 2004; Hsu, 2008; Trumper, 2006). Although students must develop model-based explanations that connect observations with underlying mechanisms, opportunities to bridge both perspectives have been limited and difficult to implement effectively (Plummer & Maynard, 2014).

Another source of difficulty lies in the educational materials used to explain the cause of seasonal changes. In most classrooms, illustrations and textual explanations from textbooks are commonly used (Galano & Testa, 2025; Mason et al., 2017). Representing three-dimensional spatial relationships between the Earth and Sun in two-dimensional illustrations inevitably introduces distortions. The eccentricity of Earth's orbit has often been exaggerated in illustrations (Testa et al., 2014), and to represent temporal progression within a single diagram, the Earth has frequently been depicted at four orbital positions - equinoxes and solstices - simultaneously (Galano et al., 2018). Such representations have been found to cause confusion for students when interpreting the illustrations, ultimately making it difficult for them to construct accurate explanations of the causes of seasonal changes (Lelliott & Rollnick, 2010).

This difficulty in interpreting illustrations leads to additional problems. Scientific explanations typically combine both visuals and text, and when students struggle to understand the visuals, they also have difficulty integrating the two forms of information. Although illustrations and text have been commonly used to enhance understanding of complex scientific concepts (Peterson, 2016), both forms have conveyed mutually dependent information, and constructing a coherent mental model requires integrating them (Ainsworth, 2006; Scheiter et al., 2017). Given the cognitive demands posed by spatially complex and information-rich illustrations of seasonal change, integrating text and visuals may place a heavy cognitive load on learners and increase the likelihood of misinterpretation (Shah & Hoeffner, 2002).

Despite the significance of seasonal change as a core scientific concept, persistent misconceptions, difficulties in perspective-taking, and limitations in educational materials continue to hinder students' conceptual understanding. Prior research has not sufficiently addressed how to effectively support students in integrating Earth-based and space-based perspectives, nor how to reduce the cognitive load imposed by conventional illustrations. This represents a critical problem in science education, as it prevents learners from constructing scientifically accurate explanations of astronomical phenomena. Therefore, it is necessary to examine whether providing explicit perspective-taking supports can overcome these challenges, improve students' visual processing, and enhance their conceptual understanding of seasonal changes.

To address these challenges, this study introduces a support element aimed at facilitating perspective-taking between space-based and Earth-based perspective when learning about the causes of seasonal change using illustrations and text. Prior studies have proposed such direct support strategies to foster the integration of perspectives (Heywood et al., 2013; Plummer, 2012, 2014; Plummer et al., 2011, 2014), which can help reduce students' cognitive load related to perspective-taking (Höffler & Leutner, 2011). Such strategies are expected to enhance students' comprehension of visual representations and improve task performance.

Nevertheless, evaluating the learning outcomes of this perspective-taking support is not straightforward, as various learner-related factors, such as prior knowledge and experience, may influence results. Therefore, this study employed an eye-tracking method, which can provide objective data on learners' cognitive processes. Eye fixation location and duration are closely associated with the mental processes involved in task performance (van Gog et al., 2009), offering empirical evidence regarding the effectiveness of perspective-taking supports.

The research questions guiding this study were as follows:

1. What is the effectiveness of a perspective-taking support element in directing students' visual attention?

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2. To what extent is the support element effective in facilitating transitions in gaze between illustrations and text?
3. How effective is the support element in enhancing conceptual understanding of the cause of seasonal changes?

Research Methodology

Design Overview

This study adopted a true experimental design with a pre-test–post-test control group. A total of 44 sixth-grade students were randomly assigned to either the experimental group (n = 22) or the control group (n = 22). The research was conducted in September–October 2023 during the second semester, when the unit on "Seasonal Changes" is taught in the Korean national science curriculum. The participants were drawn from one elementary school in Gyeonggi Province, South Korea. Although the study was limited to a single school context, the educational sequence and tasks reflected the national curriculum framework.

The research adopted a quantitative approach, combining conceptual understanding assessments with eye-tracking methodology to obtain objective measures of learners' cognitive processes. The theoretical framework draws on perspective-taking theory (Moll & Tomasello, 2006), which highlights the cognitive challenge of coordinating different viewpoints, and cognitive load theory (Chandler & Sweller, 1991), which explains how educational supports can reduce processing demands when learners engage with complex visual representations.

According to the Korean national science curriculum, the unit on "Seasonal Changes" begins with lessons focused on the relationship between solar altitude and temperature variations within a day and across a year, emphasizing Earth-based observations (see Figure 1a). Later in the unit, students explore the causes of seasonal changes by comparing Earth's positions in summer and winter using a space-based observer perspective (see Figure 1b). In this lesson, students learn that differences in the Sun's meridian altitude across seasons arise from Earth's axial tilt as it revolves around the Sun.

Figure 1
Illustrations from the "Seasonal Changes" Unit

(a) Earth-based observer view (b) Space-based observer view

To effectively understand the causes of seasonal changes, students must shift between Earth-based and space-based perspectives. First, they examine a space-based illustration (Figure 1b) to identify the differing angles of sunlight at Earth's summer and winter positions. Then, they use an Earth-based perspective to interpret the Sun's altitude at mid-latitudes, connecting this to earlier lessons in the unit.

This educational sequence encourages students to reason about solar altitude from an Earth-based perspective while viewing a space-based revolution model. This study hypothesised that embedding a perspective-taking support element into the space-based illustration would enhance students' ability to mentally coordinate between space-based and Earth-based perspectives. Providing such a support may facilitate students' inference of seasonal differences in solar altitude and promote the integration of prior educational content. Accordingly, this study examines the effectiveness of a visual perspective-taking element in supporting students' conceptual understanding.

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Participants

Eighty sixth-grade students (39 male, 41 female) from an elementary school in central Korea were initially recruited. All sixth-grade students in the school were invited to participate, and both students and their parents were informed about the non-invasive and safe nature of the eye-tracking procedure. Written informed consent was obtained from students and parents, and the study received approval from the university's Institutional Review Board (IRB).

During data analysis, eye-tracking data from 36 students were excluded because their valid fixation rate fell below the 80% threshold, a commonly applied criterion to ensure the reliability of gaze data (cf. van Gog et al., 2009). As a result, the final dataset comprised 44 students (18 male, 26 female).

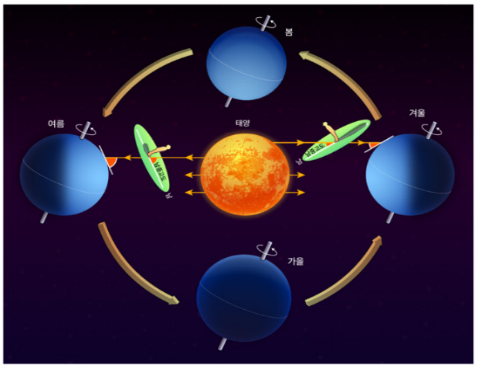
Task and Conceptual Understanding Assessment Development

The learning task was based on the lesson titled "Why Do Seasonal Changes Occur?" from the sixth-grade unit "Seasonal Changes" in the Korean national science curriculum. This task was designed to help students independently explore the cause of seasonal variation in Korea. The illustrations in the learning task were adapted from those commonly found in commercial science textbooks. They visualized the Sun, the Earth's revolution, and the Sun's meridian altitude at mid-latitudes in the Northern Hemisphere during the summer and winter positions of Earth's orbit. To minimize unnecessary cognitive load during the learning process, the eccentricity of Earth's orbital path was reduced, and Earth was represented as a simple blue sphere. Additionally, key visual elements such as Earth's axial tilt, orbital path and direction, and parallel solar rays directed toward Earth were clearly depicted to ensure the illustration was both simplified and conceptually accurate.

For the experimental group, the illustration included a visual element designed to support perspective taking: a human figure placed on Earth at the location of Korea during both summer and winter. A circle representing the ground surface was drawn, with the observer figure positioned at the centre, oriented to indicate front and back. The figure's shadow was cast by parallel solar rays, and one of the rays was extended to connect with the ground, explicitly depicting the angle of incidence between the sunlight and the surface. In contrast, the control group's illustration did not include the human figure. Illustrations were professionally created and revised three times.

The explanatory text was extracted from the most widely used science textbook currently used in schools. In the task layout, the illustration was positioned on the left side and the text on the right. The finalized versions of the experimental and control tasks are shown in Figure 2. To ensure content validity, three experts in Earth science education with experience in eye-tracking research reviewed the materials. The task was revised based on their feedback across two rounds of review, and the final Item-Level Content Validity Index (I-CVI) score was 1.0. A pilot test with six sixth-grade students (three per group) confirmed the feasibility of the task.

Figure 2
Learning Tasks for Experimental and Control Groups



계절의 변화는 지구의 자전축이 기울어진 채 태양 주위를 공전하기 때문에 생깁니다. 지구의 자전축이 기울어진 채 태양 주위를 공전하면 지구의 위치에 따라 태양의 남중고도가 달라지고, 단위 면적의 지표면에 도달하는 태양에너지의 양이 달라져 계절이 변합니다.

지구의 자전축이 기울어져 있지 않거나 지구가 태양 주위를 공전하지 않는다면 계절의 변화가 생기지 않습니다.

Experimental task

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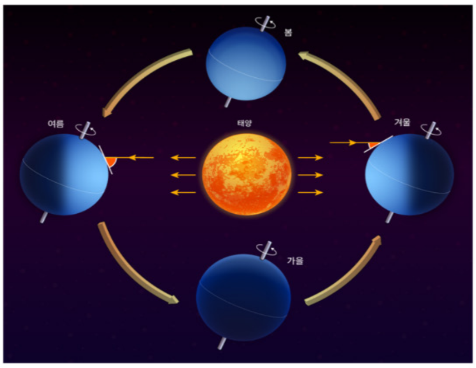

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Control task

Note. The original Korean text in the figure has been translated into English in the Appendix.

To assess students' conceptual understanding, a pre- and post-assessment was developed, in which students were asked to explain the cause of seasonal changes using both drawings and written descriptions. The assessment consisted of a single A4 page and was administered before and after the learning task.

Data Collection

The learning task was implemented during the final lesson titled "Why Do Seasonal Changes Occur?" within the "Seasonal Changes" unit. In this session, students engaged in self-directed learning to construct their understanding of the concept using the provided materials. Accordingly, data collection had to be scheduled in alignment with the educational sequence of each participating class. The unit "Seasonal Changes" is typically taught in the second semester, around October. Accordingly, the pre-test was administered in September 2023 before the unit began. After the regular lessons for the unit, the learning task and post-test were conducted during the designated lesson. An overview of the data collection process is shown in Table 1.

Table 1
Overview of the Data Collection Process

Stage	Method	Content
Pre-test	Conceptual understanding assessment	Expressing the cause of seasonal changes through writing and drawings
Preparatory lessons	Regular classroom lessons	Making a 3D model of the four seasons
		Measuring solar altitude, shadow length, and temperature throughout the day
		Exploring the relationship between solar altitude, shadow length, and temperature during the day
		Investigating the relationship between seasonal variation in solar altitude, day length, and temperature
		Exploring why temperature changes with solar altitude
Main experiment	Eye-tracking during Task performance	Why do seasonal changes occur?
Post-test	Conceptual understanding assessment	Expressing the cause of seasonal changes through writing and drawings

Prior to the unit lessons, a printed conceptual understanding assessment was administered as a pre-test. Students were given approximately 10 minutes to freely express their understanding of the cause of seasonal changes using both drawings and written explanations. During the unit, regular lessons were carried out through

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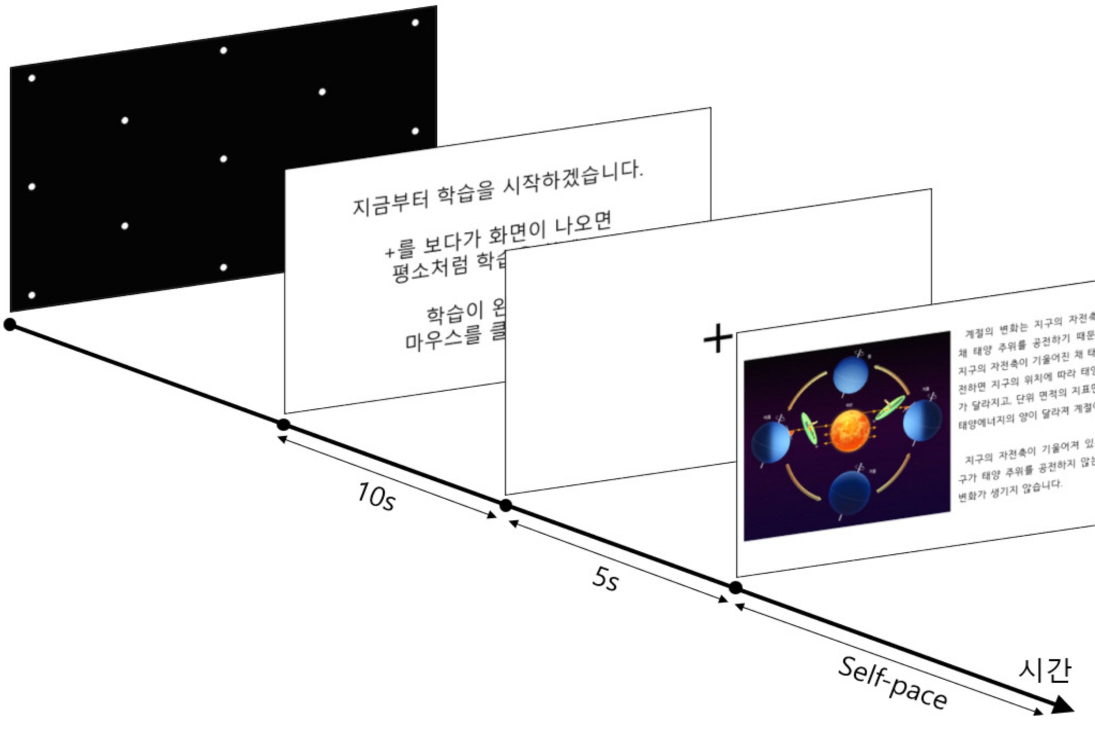
five lessons. To control for teacher-related variables, a single science teacher conducted all five lessons using the same teaching content and methods across multiple classes.

The experiment was conducted individually in a quiet, isolated room within the school, where external light and noise were minimized. To help participants concentrate, partitions were placed on both sides of the desk, and height-adjustable chairs were provided. Students were randomly assigned to either the experimental or control group using a random number table, regardless of the order in which they participated. Each participant engaged in a self-directed learning task displayed on a monitor while their eye movements were recorded using a Tobii X2-60 eye tracker mounted on the bottom of a 17-inch monitor. The eye-tracking task paradigm used in this experiment is illustrated in Figure 3.

Figure 3
Eye-tracking Task Paradigm



Upon seating, students received a brief explanation and completed a calibration process. The task sequence included a 10-second instructional screen followed by a 5-second display of a central fixation cross ("+") before the learning task appeared. There was no time limit for completing the task; participants were asked to click the mouse upon finishing. On average, task completion took approximately 5 minutes. After completing the learning task, students took a post-test using the same conceptual understanding assessment as in the pre-test, which asked them to explain the cause of seasonal changes using both drawings and written explanations.

Data Analysis

Data analysis was conducted using Tobii Pro Lab, with the minimum fixation duration set to 100 ms. Based on the research questions, the analysis was divided into three parts: visual attention to the learning task, integration between illustrations and text, and conceptual understanding.

Visual attention was examined using three specific approaches. The first analysis investigated group differences in gaze attention to key areas of the illustration. These key areas included Earth's positions during summer and winter, the Sun, and the Sun's meridian altitude depicted along Earth's orbital path. To accurately understand the concept using the illustration, students needed to identify and compare the relative position of the Sun and the difference in solar altitude between summer and winter.

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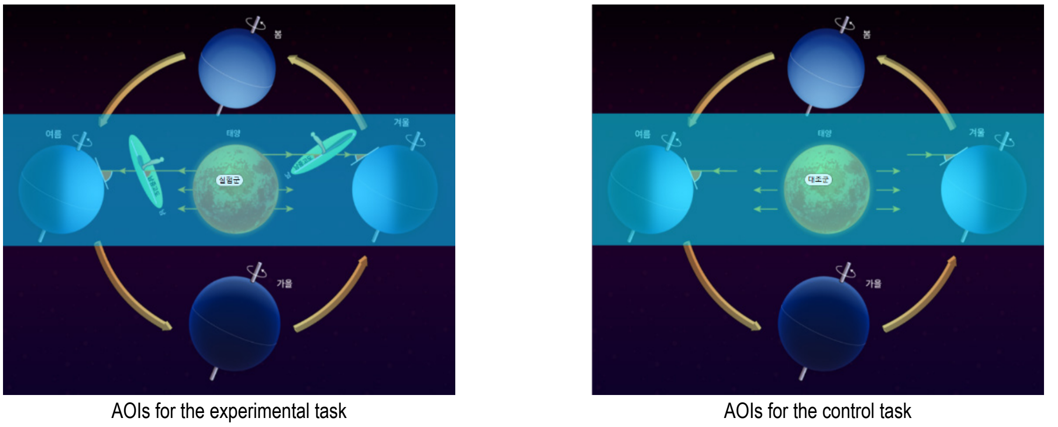
Accordingly, we examined whether the presence of a visual perspective-taking support element influenced students' gaze attention to these key parts. For this purpose, AOIs were defined around the summer and winter positions of the Earth and the Sun (see Figure 4). The proportion of total visit duration within each AOI relative to the overall task duration was used as a measure of visual attention to the key areas. Group differences were statistically analysed using the Mann-Whitney *U* test.

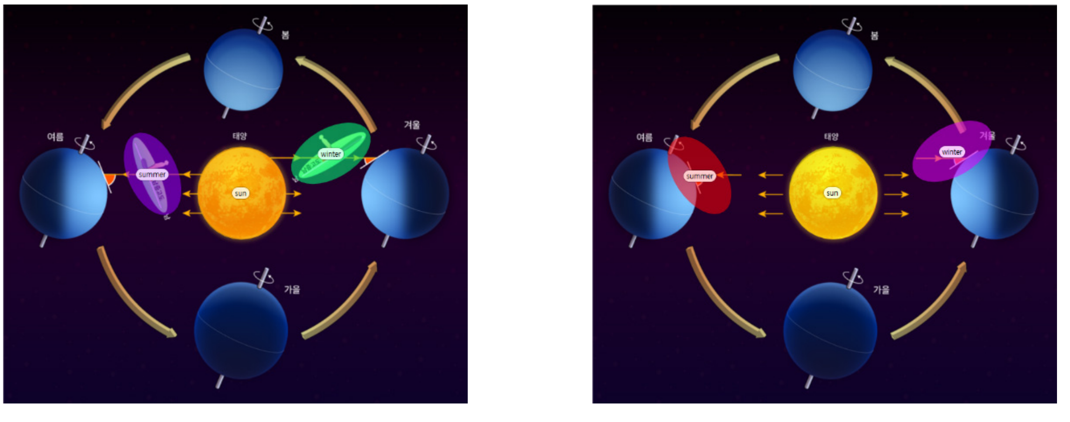
Figure 4
AOIs for Key Illustration Areas in Experimental and Control Groups



AOIs for the experimental task AOIs for the control task

Second, group differences in the number of gaze transitions between the Sun and the indicators of solar meridian altitude for summer and winter in the illustration were analysed. To understand the concept through the illustration, students needed to alternate their attention between the Sun's position and the angles formed by sunlight and the ground at Earth's summer and winter positions—an essential process that is revealed through eye movement behaviour. For this purpose, three distinct AOIs were defined: the Sun, the solar meridian altitude at the summer position, and the solar meridian altitude at the winter position (Figure 5). To ensure valid comparisons, the AOI sizes were kept identical across the experimental and control groups. All fixation coordinates were extracted in chronological order, and a gaze transition was counted when a fixation moved sequentially from one AOI to another. Consecutive fixations within the same AOI were excluded from the count. The total number of these gaze transitions between AOIs was statistically compared between the two groups using the Mann-Whitney *U* test.

Figure 5
AOIs for Analysing Gaze Transition Frequency



AOIs for the experimental task AOIs for the control task

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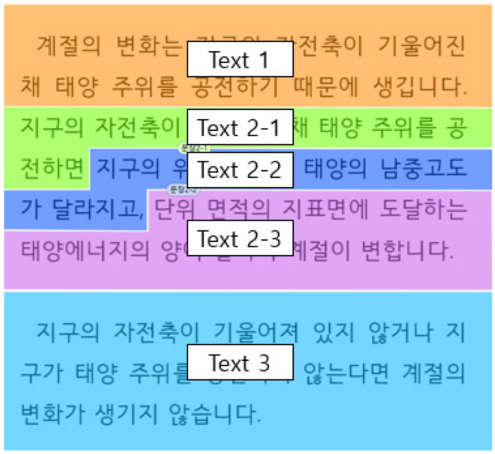
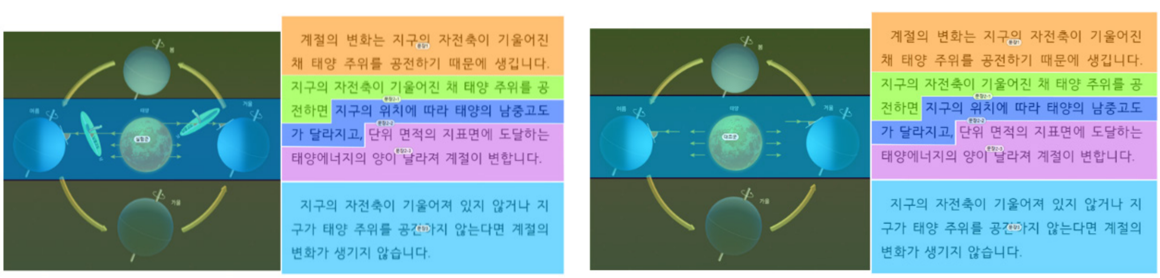
Third, we analysed group differences in the duration of visual attention allocated to each sentence in the explanatory text. To conduct this analysis, each sentence was designated as a separate AOI (Figure 6), and the total fixation duration within each AOI was calculated. Statistical comparisons between groups were performed using the Mann-Whitney *U* test.

Figure 6
AOIs for Text-based Visual Attention Analysis



To examine the patterns of integration between illustrations and text, we employed Lag Sequential Analysis (LSA), a method introduced by Bakeman and Gottman (1997). LSA allows researchers to analyse gaze transition sequences between AOIs and to calculate the probabilistic likelihood of transitioning from one fixation area to another based on the immediately preceding gaze point (Lee, 2005). This method enables researchers to infer students' reading strategies when engaging with illustrated science texts (Bakeman & Gottman, 1997; Jian, 2016). For the analysis, AOIs were defined as shown in Figure 7. Following the LSA algorithm, the analysis focused on the number of transitions between different AOIs, excluding repeated fixations within the same AOI (Bakeman & Gottman, 1997; Hsu et al., 2019). The LSA procedure followed the steps outlined by Hsu et al. (2019), and an extended version of the Data Analysis Tool ver. 1.7, originally developed by Jeong (2003), was used. Based on the frequency of gaze transitions between AOIs, a Z-score matrix was constructed. Transitions with Z-scores equal to or greater than 1.96 were considered statistically significant, and their transition probabilities were extracted. Finally, a transition diagram was created to visually represent significant AOI-to-AOI transitions, which was then used to interpret students' reading strategies.

Figure 7
AOIs for Illustration–text Transition Analysis



AOIs for the experimental task

AOIs for the control task

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In addition, students' conceptual understanding before and after the task was analysed using the concept assessment instrument, and comparisons between groups were conducted. For the analysis, eight core conceptual elements were extracted from the coding scheme developed by Testa et al. (2023) for evaluating students' drawings related to seasonal changes. Based on these elements, evaluation criteria and items were established, as shown in Table 2. Each item was scored as 1 point if the corresponding concept was present, resulting in a maximum possible score of 8. To ensure the reliability of the analysis, inter-rater agreement was calculated among four graduate students majoring in science education. The average Cohen's Kappa coefficient was .85, indicating a satisfactory level of coding consistency.

Table 2
Evaluation Criteria and Items for Pre- and Post-Test of Conceptual Understanding

Conceptual Category	Evaluation Item
Axial Tilt	Drawing or mentioning of the axial tilt
	Correct representation or explanation of the axial tilt
Solar Altitude & Energy	Drawing or explanation of changes in solar altitude or solar energy
	Accurate representation or explanation of these changes
Revolution	Drawing or mentioning of Earth's revolution
	Depiction of a Sun-centred model or description of the Earth's revolution around the Sun
	Drawing or explanation of Earth's orbit
	Inclusion or explanation of the counterclockwise orbital direction

Research Results

Effects of Perspective-Taking Support on Students' Visual Attention

The first analysis of visual attention examined group differences in attention to the core components of the illustration-specifically, the positions of Earth in summer and winter and the Sun. A Mann-Whitney *U* test was conducted to determine whether the proportion of visual attention directed to these key areas differed between the groups. As shown in Table 3, no statistically significant difference was found. This result suggests that the presence or absence of the perspective-taking support element had little effect on students' allocation of attention to the core parts of the illustration.

Table 3
Mann-Whitney U Test Results for Visual Attention to Key Illustration Areas

Group	*N*	*M*	Σr	*Z*
Experimental group	22	24.09	530.00	-.822
Control group	22	20.91	460.00	
Total	44			

The second analysis examined group differences in the number of gaze transitions between the Sun and the indicators of solar meridian altitude for summer and winter. The results of the Mann-Whitney *U* test are presented in Table 4. The experimental group exhibited a significantly higher number of gaze transitions than the control group at the .01 level. This suggests that participants in the experimental group more frequently shifted their gaze between the Sun and the altitude indicators, indicating a more active integration of key visual components necessary for understanding the concept. This finding provides evidence that the visual perspective-taking support element facilitated more effective processing of the illustration. However, it is also possible that this effect was partially influenced by the spatial proximity of the Sun and the solar altitude indicators in the experimental

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illustration, as well as the visual continuity created by connecting solar rays, which may have guided students' gaze more fluidly across related elements.

Table 4
Mann-Whitney U Test Results for Number of Gaze Transitions

Group	*N*	*M*	*Σr*	*Z*
Experimental group	22	27.14	597.00	-2.767**
Control group	22	17.86	393.00	
Total	44			

** $p<.01$

The third analysis examined group differences in the total fixation duration on each sentence of the explanatory text. A Mann-Whitney *U* test was conducted for each sentence, and the results are presented in Table 5. A statistically significant difference at the .05 level was found for Text 2-3, with the experimental group spending less time fixating on this sentence than the control group. The sentence reads: "The amount of solar energy reaching a unit area of Earth's surface changes, which causes the seasonal changes." This suggests that the perspective-taking support element may have facilitated more efficient processing and comprehension of this particular concept. No significant differences were observed for the other sentences.

Table 5
Mann-Whitney U Test Results for Fixation Duration on Text Sentences

Category	Group	*N*	*M*	*Σr*	*Z*
Text 1	Experimental group	22	20.73	456.00	-.428
	Control group	20	22.35	447.00	
	Total	44			
Text 2-1	Experimental group	22	21.89	481.50	-.214
	Control group	20	21.08	421.50	
	Total	44			
Text 2-2	Experimental group	22	21.89	481.50	-.317
	Control group	22	23.11	508.50	
	Total	44			
Text 2-3	Experimental group	22	18.20	400.50	-2.218*
	Control group	22	26.80	589.50	
	Total	44			
Text 3	Experimental group	22	18.19	382.00	-1.944
	Control group	22	25.64	564.00	
	Total	44			

* $p<.05$

Effects of Perspective-Taking Support on Illustration–Text Gaze Transition Patterns

Lag Sequential Analysis (LSA) was conducted to examine gaze transition patterns between illustration and text elements, enabling the identification of reading strategies influenced by the presence or absence of the perspective-taking support element. Tables 6 and 7 show the *Z*-score matrices for the experimental and control

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groups, respectively. These matrices statistically evaluate whether transitions between AOIs occurred by chance or represent meaningful behavioural patterns. A *Z*-score greater than 1.96 indicates a statistically significant transition at the $p < .05$ level, and such cells are shaded in the tables. For each significant cell ($Z > 1.96$), the corresponding transition probability is also shown in parentheses. This probability, ranging from 0 to 1, reflects the likelihood that a gaze shifts from one AOI to another, with higher values indicating stronger transition tendencies.

Table 6

Z-score Matrix and Transition Probabilities for Experimental Group

	Text 1	Text 2-1	Text 2-2	Text 2-3	Text 3	Key Area (Red Box)	Non-Key Areas
Text 1		7.89(.42)	-3.38	-2.45	-3.49	-2.87	-1.41
Text 2-1	3.77(.28)		6.49(.34)	-1.59	-3.62	0.32	-1.01
Text 2-2	-2.40	5.58(.36)		8.07(.34)	-1.75	-0.40	-1.19
Text 2-3	-1.80	-3.27	1.73		8.45(.39)	1.37	1.32
Text 3	-1.67	-2.87	-1.78	1.65		2.43(.20)	-0.45
Key Area (Red Box)	0.23	-1.82	3.98(.29)	-0.68	-0.68		6.90(.19)
Non-Key Areas	-0.23	-1.87	-1.66	-1.85	0.68	6.85(.50)	

Note. Only significant values shown in shaded cells where $Z > 1.96$

Table 7

Z-score Matrix and Transition Probabilities for Control Group

	Text1	Text2-1	Text2-2	Text2-3	Text3	Key Area (Red Box)	Non-Key Areas
Text1		11.11(.52)	-2.36	-3.72	-1.48	-1.99	-1.3
Text2-1	4.19(.26)		7.92(.42)	-2.46	-3.61	-1.70	-1.39
Text2-2	-1.62	1.16		8.26(.45)	-3.73	0.34	-2.17
Text2-3	-3.31	-3.81	3.32(.25)		9.34(.42)	0.58	-1.12
Text3	-0.77	-2.99	-2.93	2.72(.28)		2.44(.14)	3.73(.10)
Key Area (Red Box)	1.84	0.00	-0.67	-0.37	1.12		5.22(.16)
Non-Key Areas	-0.81	-1.50	-1.63	-1.32	1.34	6.93(.42)	

Note. Only significant values shown in shaded cells where $Z > 1.96$.

Figures 9 and 10 visually represent the statistically significant transition probabilities extracted from Tables 5 and 6, respectively. Arrows indicate significant gaze transitions, and the accompanying numbers represent the corresponding transition probabilities. Figure 8 shows the gaze transition pattern of the experimental group. In this group, frequent transitions were observed between the key components of the illustration (highlighted in red in Figure 8) and core textual elements, particularly Text 2-2 ("The solar altitude varies depending on Earth's position"), Text 2-3 ("The amount of solar energy received per unit area changes, which causes seasonal change"), and Text 3 ("If Earth's axis were not tilted or if Earth did not revolve around the Sun, there would be no seasonal change"). These cyclic gaze patterns suggest that the visual perspective-taking support effectively encouraged integration between the critical illustration and relevant text components. The absence of regressions to earlier sentences indicates that students did not struggle with understanding the conceptual content.

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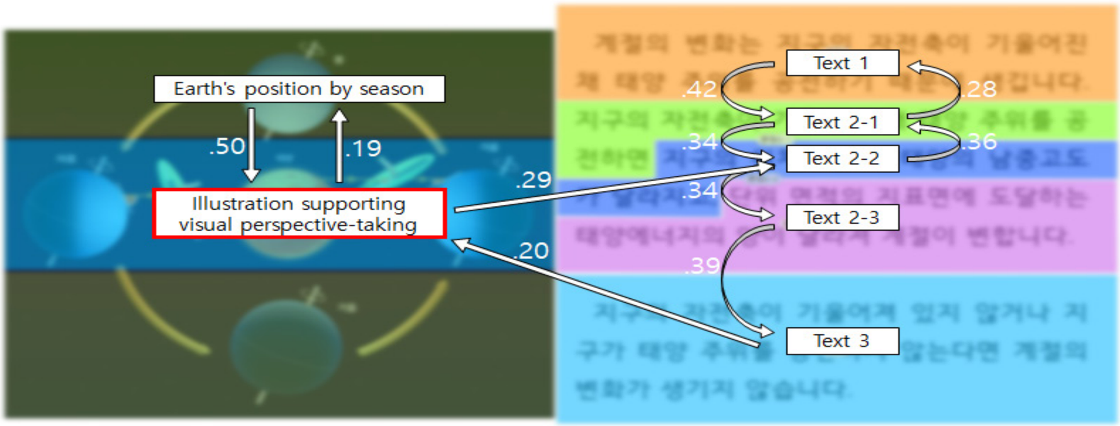
Figure 8

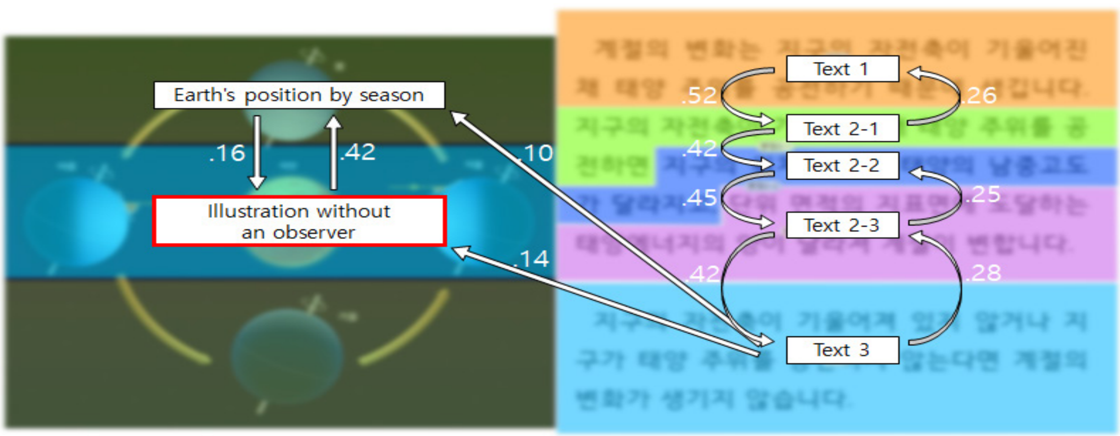
Gaze Transition Pattern - Experimental Group



In contrast, Figure 9 presents the gaze transition pattern of the control group, showing a clear tendency to move to the illustration only after reading the entire text. The transitions from the final text segment to the illustration were unidirectional, with low transition probabilities (.10 and .14), indicating a lack of integrative cognitive processing between text and illustration. These findings suggest that the control group processed the task less efficiently, treating the text and the illustration as separate components. Additionally, transitions toward the key parts of the illustration (highlighted in red in Figure 9) were less frequent compared to the experimental group. More frequent regressions to earlier sentences in the main text were also observed, suggesting that students in the control group experienced greater difficulty in understanding the conceptual explanations.

Figure 9

Gaze Transition Pattern - Control Group



Effects of Perspective-Taking Support on Conceptual Understanding

Pre- and post-tests of conceptual understanding were administered to both the experimental and control groups. Independent samples t-tests were conducted to examine group differences in scores (Table 8). The results revealed no significant difference in the pre-test scores, suggesting that the two groups were comparable in their initial level of conceptual understanding. However, a statistically significant difference was found in the post-test scores at the .01 level, with the experimental group scoring higher than the control group. These findings suggest that the learning task incorporating the visual perspective-taking support element was more effective in enhancing students' conceptual understanding.

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Table 8
Independent Samples T-Test Results for Conceptual Understanding Scores

Test	Group	*n*	*M*	*SD*	*t*
pretest	Experimental group	22	7.59	5.90	.025
	Control group	22	7.55	5.96	
posttest	Experimental group	22	20.00	9.53	3.38**
	Control group	22	11.86	6.04	

** $p<.01$

Discussion

This study examined the effectiveness of incorporating a perspective-taking support element to help elementary school students more effectively process a learning task about the causes of seasonal changes. Eye-tracking methodology was employed to examine how the support influenced students' visual attention, gaze behaviour, and conceptual understanding. The results showed no significant group differences in the proportion of visual attention directed to the key parts of the illustration, regardless of the presence of the support element. However, significant differences were observed in other aspects: the number of gaze transitions, total fixation durations on specific text segments, gaze transition patterns between text and illustration, and post-task conceptual understanding scores. These findings suggest that the perspective-taking support did not affect how attention was distributed across visual elements but rather influenced the qualitative aspects of cognitive processing—such as how students interpreted and integrated the information presented. In other words, the perspective-taking support influenced how students processed and connected the visual and textual information, leading to deeper conceptual understanding.

Specifically, a significant difference was found in the number of gaze transitions between the Sun and the solar meridian altitude indicators depending on the presence of the perspective-taking support. To accurately grasp the seasonal differences in solar altitude using the illustration, students need to actively examine the angles formed between the sunlight and the ground. Gaze transitions between these key elements are considered indicators of successful information processing (O'Keefe et al., 2014). Although the two groups were presented with similar visual information, the experimental group exhibited more frequent transitions, suggesting that the perspective-taking support element promoted more effective processing of the illustration.

Furthermore, a significant difference was found in the fixation duration for Text 2-3, with the experimental group showing a shorter fixation time. This suggests that less cognitive effort was required to understand this sentence, likely due to the contextual framework already established through Text 2-1 and Text 2-2, which explained how Earth's revolution causes variations in solar altitude. Text 2-3 builds on this by stating that seasonal changes occur due to differences in the amount of solar energy reaching Earth's surface. Generally, increased cognitive load is associated with longer fixation durations (Ozcelik et al., 2010; Rayner, 1998). The shorter fixation duration in the experimental group implies that the sentence was more readily integrated into their existing mental model, indicating that the perspective-taking support element may have facilitated more efficient text processing.

One of the most salient findings of this study was the clear difference in the integration patterns between text and illustration depending on the presence of the perspective-taking support element. For students to construct a sophisticated mental model of the content, it is essential that they integrate textual and visual information into a coherent representation (Ainsworth, 2006; Scheiter et al., 2017). Such integration requires learners to identify and connect related elements across text and illustration while operating within the limits of cognitive capacity (Schnotz et al., 2014; Scheiter et al., 2017). The gaze transition patterns captured through eye-tracking revealed how each group engaged in this integrative learning process.

The control group exhibited a sequential processing pattern in which students tended to process the text in its entirety before attending to the illustration. This pattern is commonly observed among novice learners (Hegarty & Just, 1993; Jian & Ko, 2017; Johnson & Mayer, 2012; Schmidt-Weigand et al., 2010; Schnotz et al., 2014). In such cases, learners typically allocate their initial attention to the text to form a preliminary understanding, and then attempt to locate and integrate relevant elements from the illustration based on that foundation (Schmidt-Weigand et al., 2010; Schnotz et al., 2014). However, this approach may result in either minimal attention to relevant parts of

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the illustration or superficial processing, making it difficult to construct a fully integrated mental model (Hannus & Hyönä, 1999; Schnotz et al., 2014). Additionally, the control group exhibited notable regression to earlier sentences, a pattern of text-centred gaze behaviour that suggests an attempt to construct an initial understanding solely from the text before engaging with the illustration (Scheiter & Eitel, 2017). This regressive pattern implies difficulties in forming integrated representations using the text alone (Goldman & Saul, 1990), highlighting that deep conceptual processing is unlikely to occur without meaningful reference to the accompanying visuals (Jian, 2016; Jian & Ko, 2017).

In contrast, the experimental group demonstrated a cyclical pattern of attention between the text and the illustration, suggesting a gradual construction of a coherent mental model through integrative processing. Given that the task presented information in both textual and visual formats, it constituted a cognitively demanding stimulus. To process this effectively, students had to retain parts of the textual content in their working memory (Chandler & Sweller, 1991) while concurrently identifying and integrating related visual elements from the illustration (Kaplan & Erden, 2008). This process requires substantial cognitive effort, but the mutual reinforcement between text and illustration helps deepen comprehension (Seufert, 2019). Accordingly, repeated transitions between text and illustration facilitate the construction of a more consistent and coherent mental representation (Jian, 2016; Jian & Ko, 2017; Schnotz et al., 2014; Schüler, 2017).

In addition, although there was no significant difference in the pre-test scores of conceptual understanding between the experimental and control groups, the post-test revealed a statistically significant gap, indicating that the two groups processed the task in qualitatively different ways. Based on this result, it can be inferred that the presence of the perspective-taking support element led to a shift in students' information processing strategies during the task of learning about the causes of seasonal change. To interpret the illustration explaining seasonal change, students are required to make an inferential shift from the space-based model of Earth's revolution to an Earth-based observer's perspective on the Sun's meridian altitude. This shift is cognitively demanding, especially when students are not given sufficient time or support to make the transition (Plummer & Maynard, 2014). In this respect, the perspective-taking support element served as a cognitive scaffolding tool. It went beyond a decorative role by embedding the viewpoint of an observer into the illustration, helping students reconstruct their understanding from the Earth-based frame they had encountered in earlier lessons. This allowed them to more effectively interpret the visual information and integrate it with prior knowledge.

Additionally, the perspective-taking support appears to have functioned as a perceptual cue that facilitated the integration of text and illustration. Successful integration requires learners to appropriately map related elements across different representations (Schnotz et al., 2014). As seen in the experimental group's gaze transition patterns (Figure 9), the perspective-taking support element was visually salient within the illustration, effectively capturing students' attention. Such perceptually prominent features tend to draw visual attention easily (Underwood & Foulsham, 2006) and, in this context, highlighted the key concept of seasonal differences in solar meridian altitude. By doing so, the support likely promoted more effective connections with the relevant textual information.

However, this study has a limitation in that it could not directly determine whether students were guided by the perspective-taking support element to adopt an Earth-based viewpoint from a mid-latitude position and represent solar meridian altitude accordingly. To obtain explicit evidence of students' perspective-taking, verbal data such as think-aloud protocols would be necessary. However, elementary school students often face difficulties in verbalising their cognitive processes (van Someren et al., 1994), and the act of verbalisation itself may interfere with learning. To compensate for this limitation, the present study employed eye-tracking as an objective method to capture students' cognitive processing during task performance (van Gog et al., 2009), thereby providing empirical evidence for the benefits of embedding perspective-taking supports in illustrations. In addition, the relatively small sample size reflects the practical limitations of applying eye-tracking methodology with elementary school students, which restricts the generalisability of the findings. Moreover, as the study focused exclusively on Korean students, the cultural specificity of the context may limit the applicability of the results to other populations. Future research should therefore include larger and more diverse samples and conduct cross-cultural comparisons to further validate and extend these findings.

Conclusions and Implications

This study examined the effectiveness of embedding a perspective-taking support element to assist students in learning the causes of seasonal changes. Eye-tracking methodology was employed to investigate visual attention, gaze transitions between illustrations and text, and conceptual understanding. The findings provide clear

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evidence of the effectiveness of the perspective-taking support element, demonstrating its impact on students' cognitive processing.

The results showed that although there was no significant difference in overall visual attention to the key areas of the illustration, significant effects were observed in the number of gaze transitions between critical visual elements and in fixation durations on specific text segments. In terms of gaze transition patterns, the experimental group exhibited cyclical shifts between key sentences and corresponding illustrations, reflecting active integration of information. By contrast, the control group employed a more linear and less efficient strategy, processing the text first and only then attending to the illustration. These results indicate that the perspective-taking support helped students map related elements more effectively, thereby facilitating smoother and more efficient task performance. Furthermore, although the groups did not differ in pre-test conceptual understanding, the experimental group scored significantly higher on the post-test, indicating the educational effectiveness of the support in facilitating students' construction of scientific explanations.

Taken together, the findings provide empirical evidence that incorporating perspective-taking support elements leads to qualitatively different cognitive processing during science learning tasks. These supports facilitated students' comprehension of the illustrations, enabled more effective integration of visual and textual information, and helped them construct coherent mental models. The results underscore the importance of visual design strategies that naturally elicit perspective-taking-especially in tasks requiring spatial reasoning. Moreover, eye-tracking proved to be a powerful tool for gaining insights into how students process visual information, offering practical implications for the development of future educational materials in science education. Future research could extend these findings by exploring how perspective-taking supports influence student understanding of other space-related concepts-such as lunar phases or the Sun's apparent motion due to Earth's rotation—thus broadening the generalizability of this approach.

Conflict of Interest

The author(s) declared no conflicts of interest.

Acknowledgements

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Appendix

English Translation of Korean Text in Figure 2

"Seasonal changes occur because the Earth revolves around the Sun while its rotational axis is tilted. Due to this tilt, the Sun's altitude at noon varies depending on the Earth's position in its orbit, resulting in differences in the amount of solar energy received per unit area on the Earth's surface. These variations cause the seasons to change.

If the Earth's rotational axis were not tilted or if the Earth did not revolve around the Sun, seasonal changes would not occur."

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BASIC INQUIRY AND INTEGRATED SCIENCE PROCESS SKILLS IN DIGITAL-RELATED EXPERIMENTS WITHIN PHYSICS TEXTBOOKS OF SOUTH KOREA, THE UNITED KINGDOM, AND INDONESIA

Ni Wayan Rai Utari Dewi, Minchul Kim

Abstract. *Technological development, particularly in experimental, is now embedded in physics textbooks. Therefore, this study analyzed how the basic inquiry and the integrated science process skills in digital-related experiments are distributed within physics textbooks of South Korea, the United Kingdom, and Indonesia. A descriptive qualitative content analysis was conducted by analyzing physics textbooks from these countries. The samples included six physics textbooks, two from each country. The findings indicate that the most frequently used digital-related experiment tool was the video recorder in South Korea, the computer in the United Kingdom, and the virtual (simulation) experiment in Indonesia. The distribution of basic inquiry skills from these countries predominantly emphasizes 'observing' and 'measuring', while other skills are only minimally incorporated. However, the 'classifying' and 'predicting' were not found in any textbooks. Furthermore, the distribution of integrated science process skills shows that 'experimenting' skills are used most frequently, while the other skills are only minimally incorporated. However, 'formulating hypotheses' was not found in any textbooks. Therefore, this study strongly emphasizes the digital-based experiments, which highlight the optimization of basic inquiry and integrated science process skills distribution. This study can be used as a reference in developing educational policy or curriculum on a global scale.*

Keywords: *basic inquiry skills, integrated science process skills, digital experiment*

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Introduction

Technology has had a profound impact worldwide in this era of globalization. These days, a popular topic, Artificial Intelligence (AI), is gaining much attention because of its convenience. This discovery contributes to various fields in this digital era. It has been proved that technology influences the life aspect of humans. Digitalization has a significant role in many fields, particularly the education field. In the education field, the utilization of technology is commonly adopted by teachers and students. For instance, PowerPoint is used to present the materials of physics material in the school, which also constructs learning engagement with students. Moreover, in this era, students are highly skilled in managing technology, which aids their study. In the education environment, the learning process is more entertaining when technology is integrated (Ghory & Ghafory, 2021). This study has shown that the integration of technology into the learning process is interesting for students. Besides that, visualizing abstract scientific learning and phenomena can be implemented using digital technology, which assists students in understanding the contextual meaning (Walan, 2020). Moreover, regarding the science curriculum, awareness of the complex relationship between technology, science, environment, and society becomes a major value of learning goals (Hodson, 2020). Furthermore, Science, Technology, and Society (STS) in education have several goals, including providing science and technology literacy and equipping the future generation with the ability to master digital tools and information related to science and technology in a global society (Kumar & Chubin, 2000). This highlights the importance of technology integration within the learning stages in the school. Furthermore, in the current labor market demand, whether in research or private enterprises, the ability to operate technology has become a new requirement in physics education (Lahme et al., 2023).

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According to development experts and policymakers, most of them agree that establishing the science and technology capacity assists developing countries in generating the essential social networks for development, particularly in the globalization era (Wagner et al., 2001). The United Kingdom and South Korea are included as scientifically advanced countries on a science and technology composite index, which means these countries have greater science and technology capacity than the international mean (Wagner et al., 2001). In contrast, Indonesia is considered a scientifically developing country on a science and technology composite index, which has an overall scientific capacity below the world average (Wagner et al., 2001). It is consistent with the result of the Programme for International Student Assessment (PISA) in 2022, which reveals that the mean score of science performance in South Korea and the United Kingdom reached a mean score above the Organization for Economic Co-operation and Development (OECD) average, while Indonesia positioned below the OECD average. The mean score in South Korean students' science performance is categorized as a high score among eastern regions, and the United Kingdom also has a high score above the OECD average among western regions. These countries are classified as developed in terms of science development. In contrast, Indonesia, as a developing country, falls behind. This gap in the performance of science and its relationship with the development of a country could be grounded in the aspect of how these countries embedded the connection between science and technology in the educational context, especially in their school textbooks. One of the subjects of science that makes a major impact is physics. The disparity of this gap can be seen in the way each country delivered the materials of physics through their physics textbooks.

Every country has created its distinct educational system, resulting in varied approaches to learning experience designs, including the coverage of experimental design within textbooks (Huang et al., 2022). The utilization of technology can be implemented or incorporated into physics textbooks. Textbooks have a pivotal role in student learning instruction and as a guiding book for teachers to conduct the learning process. Students, who are provided with textbooks, not only rely on the teacher for teaching, but they can also study independently, following the steps within the textbooks. The presence of digital-related experiment tools can assist study during self-regulated learning. In addition, these digital-related experiments provide the same opportunity in the learning process, even though their school lacks laboratory tools or has to avoid dangerous equipment. Digital representations of various forms are tried out to enhance students' sense-making to fill the void between lab experiments and the laws of science (Kluge, 2014). Digital-related experiment tools include virtual simulations, interactive software, and online experiments, which allow students to conduct experiments and interact with concepts in a safe and controlled environment. Using these digital-related experiments, students can engage in real-world situations that involve experiments related to laboratory instruments.

In the past, students learned through analog experiments that involved direct basic inquiry and integrated science process skills. This process trained students to use scientific instruments directly and fostered the development of science process skills. However, these analog tools have now been replaced by digital instruments, which may also influence students' science process skills. When using digital tools, it is unclear whether students' ability to measure directly is still being developed, as digital tools often display results automatically without requiring the same measurement process as analog tools. An initial step in evaluating science process skills within digital experiments is to conduct an analysis of physics textbooks. Harlen (1999) has emphasized that science process skills are essential for developing students' scientific reasoning and should be explicitly included in the teaching and assessment of these skills through educational materials such as textbooks. Chiappetta and Koballa (2010) have explained that science textbooks should include inquiry-based activities and experiments that encourage students to apply the science process skills. However, the effectiveness of developing science process skills can vary depending on how well the digital components are aligned with the intended learning objectives. In the case of integrating technology into physics textbooks, especially in experimental activities, science process skills need to be embedded to enhance students' scientific skills, ensuring that they can conduct experiments as effectively as they would in hands-on experiments without technological assistance. Science process skills are divided into two categories: basic inquiry skills and integrated science process skills (Sermsirikarnjana et al., 2017). The presence of basic inquiry skills and integrated science process skills in physics textbooks that discuss digital-related experiments is a crucial aspect of fostering students' scientific abilities. Analyzing whether the distribution of basic inquiry skills and integrated science process skills has been allocated in these digital-related experiments is essential. Many studies analyzed the science process skills within textbooks. However, there are limited studies regarding how basic inquiry and integrated science process skills in digital-related experiments are embedded within physics textbooks across different educational systems. Therefore, examining the basic inquiry and integrated science process skills in digital-related experiment tools in upper-secondary physics textbooks in South Korea, the United Kingdom, and Indonesia is necessary.

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Research Aim and Research Questions

The purpose of this study was to investigate how digital-related experiments are distributed within physics textbooks in South Korea, the United Kingdom, and Indonesia. This research analyzed how basic inquiry and integrated science process skills in digital-related experiments are distributed within physics textbooks of South Korea, the United Kingdom, and Indonesia.

The research questions in this study were formulated as follows.

1) How are the digital-related experiments distributed in the upper-secondary physics textbooks of South Korea, the United Kingdom, and Indonesia?
2) How is the distribution of basic inquiry skills in the physics textbooks of South Korea, the United Kingdom, and Indonesia?
3) How are integrated science process skills distributed in the physics textbooks of South Korea, the United Kingdom, and Indonesia?

Research Methodology

General Background

This study applied a descriptive qualitative research design. The summary, in the form of text, words, and short phrases, is labeled as data in the descriptive qualitative research design (Miles et al., 2014). The content analysis method used in this study analyzes the textbook documents in terms of text. Berelson (1952) has stated that, according to a certain coding rule, a methodical and reducing abundant text process into a smaller number of categories is outlined as a content analysis method. The objective of qualitative content analysis is to systematically reshape several words into a concise summary (Erlingsson & Brysiewicz, 2017). The inductive content analysis method is adopted to organize the content for descriptive purposes. In this study, inductive content analysis is adopted, which allows categories and themes to emerge naturally from the data rather than being predetermined. This is suitable for exploring new perspectives, particularly in understanding how digital experiments and science process skills are embedded in textbooks. Establishing the objectives as a foundation strategy for assessing qualitative data is mentioned as an inductive approach (Thomas, 2003). The framework established is used to interpret and categorize the results of the document analysis, which are presented in Tables 3 and 4. After developing the framework, the textbooks were coded according to the predefined categories and indicators for analysis, as shown in Figures 2,3, and 4. After the textbooks were coded, the trends that emerged within them were analyzed and classified depending on the framework that had been created.

The validity of this study was the theoretical framework foundation and expert validation. The creation of a framework based on the theoretical theories mentioned in the digital-related experiment framework, as presented in Tables 3 and 4. The framework was created with relevance to the other theories, literature, and research papers. Moreover, an expert in the field of physics education was invited to ensure the framework is valid for the analysis of the document using the content analysis research method. In this step, the researcher provided the framework in advance and reviewed it with the expert. The feedback given by the expert was used to assess the consistency of the created framework and the content analysis results. The validity of the fixed framework and the results of content analysis were then validated by the expert. Feedback from the expert helped identify unclear, redundant, and missing analysis indicators in the basic inquiry and integrated science process skills. This stage assisted in the comprehensive analysis of full physics textbooks. In this phase, it guided the consistency and accuracy of the framework's process-making, coding, and analysis content, which corresponds to a learning process conducted in the school. Using a combination of the theoretical framework and expert feedback, this research ensures its validity in finding the results.

Analysis Procedure

The document analysis procedure in this study is illustrated in Figure 1. The stages of data collection and document analysis were provided. The document analysis procedure started with preparing and collecting physics textbooks from South Korea, the United Kingdom, and Indonesia.

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Figure 1
Document Analysis Procedure

Step 1	Preparation	Preparing and collecting physics textbook documents from South Korea, the United Kingdom, and Indonesia.
	⇩	
Step 2	Review of physics textbooks documents	Once the physics textbooks' documents were prepared, the researchers reviewed them to identify the items that would be examined in this study. The item of digital-related experiment is analyzed, including basic inquiry skills and integrated science process skills within this experiment.
	⇩	
Step 3	Creating the theoretical framework	After reviewing the physics textbook document that includes digital-related experiments, the researchers identified and defined a theoretical framework based on references from other research papers. Researchers classified the framework into basic inquiry skills and integrated science process skills. As a result, this classification was decided and used as the foundational tool in this study, as shown in Tables 3 and 4.
	⇩	
Step 4	Document analysis	An analysis was conducted on the digital-related experiment within the upper-secondary physics textbooks documents of South Korea, the United Kingdom, and Indonesia, according to the theoretical framework developed in the previous stage.
	⇩	
Step 5	Data interpretation	After analyzing the documents, the results were compiled and interpreted.

Country Selection

The selection of physics textbooks was also based on the selection of countries referencing the science performance, which reflects the ability and skills in science. South Korea and the UK were chosen as developed countries with high science performance. At the same time, Indonesia represents a developing country with a lower PISA score, highlighting contrasts in science education approaches. This approach can show the gap differences in the use of digital tools in physics experiments between these countries. According to the PISA Result 2022, the countries were selected based on their science performance mean score, which is presented as follows.

Table 1
Country Selection

Countries	Mean Score	OECD score average	Countries classification
South Korea	528	Countries/economies with a mean performance/share of top performers above the OECD Average	Developed country (Eastern)
United Kingdom	500	Countries/economies with a mean performance/share of top performers above the OECD Average	Developed country (Western)
Indonesia	383	Countries/ economies with a mean performance/share of top performers below the OECD average	Developing country

**Note*: average OECD mean score in science is 485 points

According to Table 1, the data from the PISA 2022 results regarding the mean scores of science performance, as published by the OECD, were presented. The table illustrates that South Korea and the United Kingdom were among the countries with mean science scores above the OECD average, which is 485 points. Specifically, South

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Korea achieved a mean score of 528, making it one of the top-performing countries/economies in science. This score indicated a significantly higher proportion of top-performing students compared to the OECD average.

In comparison, the United Kingdom obtained 500 points as the mean score, which is slightly lower than South Korea, but is above the OECD average. South Korea was selected because, in Asia, it reached a high mean score in science, which was also a representation of the Eastern region. In comparison, the United Kingdom was selected as representative of the Western region, which also reached a high score of science performance. Furthermore, both South Korea and the United Kingdom were considered developed countries, which supports a comparison between the two regions with advanced educational infrastructures. Not only countries from developed countries, but also countries from developing countries, were chosen, each with a different education system. Indonesia was selected as a representative of a developing country. Since most Western countries were considered developed and generally had relatively high mean scores, while many Asian countries were below the OECD average, only one developing country, Indonesia, was selected for this study. According to the PISA 2022 results, Indonesia's science performance mean score was below the OECD average, positioning it as a case for analyzing how science education and inquiry skills are represented in developing countries.

Textbooks Designation

Physics textbooks for upper secondary were chosen in this study according to the level of students who started learning physics as a subject and the latest published textbooks. The selection of these six physics textbooks from South Korea, the United Kingdom, and Indonesia was conducted using purposive sampling. The selection of textbooks in this study was based on purposive sampling with the intention of capturing materials that are most representative of the national curriculum implementation in each country. Specifically, physics textbooks for upper-secondary) were chosen according to the grade level where physics is formally introduced as a distinct subject, and the most recent editions available to reflect current curriculum guidelines. In addition, the selected textbooks are those most commonly used in schools, making them representative of general classroom practice within each country. The textbooks used in this study are presented below.

Table 2
Physics Textbooks Designation

Country	Textbooks Title	Author	Publisher	Year	Age
South Korea	Upper-secondary Physics I	Son, J., Lee, B., Moon, H., Park, S., Lee, S., & Jeon, B.	Visang Education	2018	15-19
	Upper-secondary Physics II				
United Kingdom	Cambridge IGCSE Physics Fourth Edition	Kennett, H., & Duncan, T.	Hodder Education	2021	14-16
	Physics for Cambridge International AS & A Level Coursebook	Sang, D., Jones, G., Chadha, G., & Wood-side, R.	Cambridge University Press	2022	16-19
Indonesia	Physics for Upper-secondary Grade 11	Radja wane, M. M., Itabuna, A., & Jono, S.	Ministry of Education, Culture, Research, and Technology	2022	16-18
	Physics for Upper-secondary Grade 12	Sarah, L. L., & Suwarmin, I. R.			

According to Table 2, the textbooks were selected based on the Upper-secondary grade, particularly the physics textbooks. The six physics textbooks were chosen randomly among many publishers. The physics textbooks that were analyzed from South Korea were 'Upper-secondary Physics I and II'. From the United Kingdom, 'Cambridge IGCSE Physics Fourth Edition' and 'Physics for Cambridge International AS & A Level Coursebook' were chosen. From Indonesia, the 'Physics for Upper-secondary Grade 11 and 12' was analyzed. The physics subject is generally taught at the Upper-secondary level, which was chosen as the object of analysis. At the high school Upper-secondary level, through physics subjects, basic inquiry, and integrated science process skills must be embedded.

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Digital-related Experiment Framework

The analytical framework in this study was compiled from various sources and references, including journal research, research institutes, and discussions among researchers who participated in this study. In this study, the distribution of basic inquiry and integrated science process skills within the digital-related experiment was analyzed. The framework in this study is divided into two parts involving basic inquiry and integrated science process skills. National Research Council (1996) has stated that basic inquiry skills have multifaceted activities that involve making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Fradd et al. (2015) have explained that basic inquiry skills include questioning, planning, implementing, concluding, and reporting. Basic inquiry skills contain skills including observation, classifying, measuring, calculation, using space/time relationships, communicating, inferring, and predicting (Sermsirikarnjana et al., 2017). Padilla (1986) has listed basic science process skills as observing, inferring, measuring, communicating, classifying, and predicting. Walters and Soyibo (2001) have given examples of basic inquiry skills, including observing, classifying, measuring, and predicting. According to these researchers, the analytical framework of basic inquiry skills was created as shown in Table 3.

Table 3
Indicators for Analyzing the Basic Inquiry Skills

Basic Inquiry Skills	Description	Indicators for analysis
Observing	Collecting data about information, objects, or phenomena through sensory perception	• Identifies the digital sensors, function, software, or simulations used in the experiment. • Recognizes changes in digital readouts (e.g., temperature, voltage, speed).
Questioning	Posing questions to explore phenomena, formulating hypotheses, and guiding the investigation	• Encouraging students to formulate questions based on observation regarding simulation or using digital experiment tools • Providing structured questions to guide students through experimentation using digital tools
Classifying	Categorizing items or events according to common characteristics	• While using digital tools, able to classify an object, data, or information related to the experiment (e.g., motion sensors). • Categorizes different types of objects or information using digital data (e.g., numerical vs. graphical).
Measuring	Determine length, volume, or mass using standard or non-standard units	• Uses digital measuring tools accurately (e.g., digital calipers, oscilloscopes). • Compares the precision of digital and analog measurements.
Inferring	Creating logical and reasonable conclusions from observed data	• Draws conclusions based on the data obtained from digital tools • Interprets errors or anomalies in sensor readings or other digital tools.
Predicting	Predicting future events based on patterns or previous experiences	• Uses simulation software to predict future outcomes in physics experiments. • Identifies patterns in real-time data shown in digital tools for making forecasts.
Communicating	Explaining results through words, graphs, or illustrations, and communicating with peers or teachers during the experiment	• Presents experimental results using digital graphs, charts, or reports (e.g., MS Excel, etc.). • Uses computer software to model and explain physics concepts.

Furthermore, according to Sermsirikarnjana et al. (2017), integrated scientific process skills contain skills such as formulating hypotheses, defining operationally, identifying and controlling variables, experimenting, interpreting data, and making inferences. Padilla (1986) has defined integrated science process skills as controlling variables, defining operationally, formulating hypotheses, interpreting data, experimenting, and formulating models. Integrated science skills were divided into identifying and defining variables, collecting and transforming data, constructing tables of data and graphs, describing relationships between variables, interpreting data, manipulating materials, formulating hypotheses, designing investigations, drawing conclusions, and generalizing (Walters & Soyibo, 2001). According to these researchers, the analytical framework of basic inquiry skills was created as shown in Table 4.

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Table 4

Indicators for Analyzing the Integrated Science Process Skills

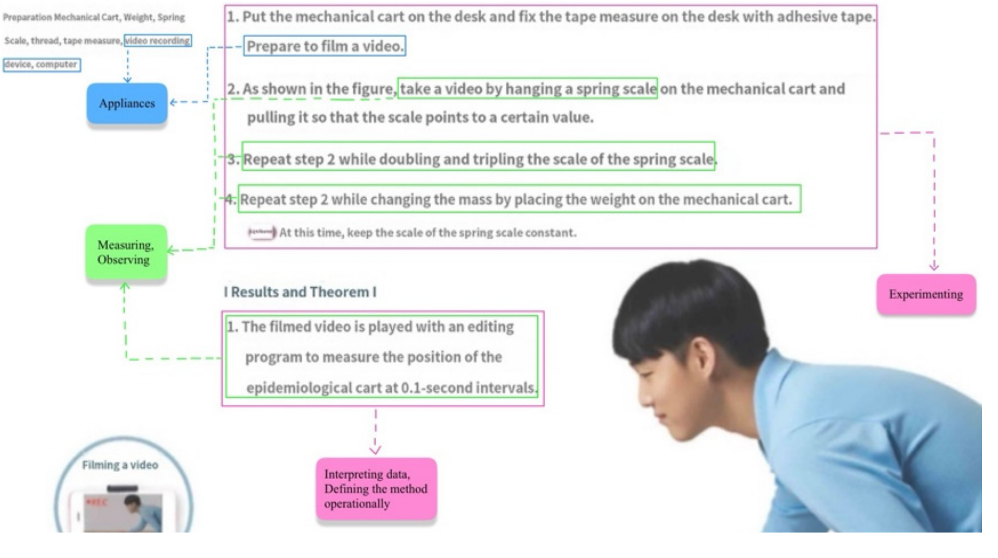
Integrated Science Process Skills	Description	Indicators for analysis
Identifying problems and variables	Recognizing problems and variables that influence the experiment results related to the utilization of digital tools	• Identifies problems in the experiment related to the utilization of digital tools • Defining independent, dependent, and controlled variables in digital-related experiments
Defining the method operationally	Defining the method for measuring a variable in an experiment	• Explains how digital tools (e.g., motion sensors, virtual lab software) measure variables like velocity, force, or temperature • Differentiates between direct sensor readings and computed values
Formulating hypotheses	Formulating and presenting hypotheses about the expected outcome of the experiment	• Predicts outcomes based on digital models or sensor data • Uses physics principles to justify expected trends in real-time digital data
Interpreting data	Arranging data and deriving conclusions	• Organizes the numerical, qualitative, or graphical data from digital tools • Analyzes trends and anomalies within simulations, digital tools, or sensor reading
Experimenting	Having the ability to conduct an experiment	• Designs or executes experiments utilizing digital tools (micro-based laboratory, etc.) • Ensures the accuracy of digital measurements and compares with theoretical calculations
Formulating model	Making a conceptual or physical model of phenomena or events.	• Creates computational models or simulations to represent physics concepts (e.g., motion, circuits, wave behavior). • Validates digital models by comparing simulated results with real-world data.

Document Analysis

Physics textbooks from South Korea, the United Kingdom, and Indonesia were analyzed using content analysis according to an established framework. In an experimental setting, the basic inquiry or integrated science process skills were counted as one skill if they emerged more than once. For instance, if the 'measuring' skills appear in steps 1,2, and 3, it was counted as one 'measuring' skill per experiment title. The example of the analysis of data from South Korean Physics Textbooks was taken from Upper-secondary Physics I. The title of the experiment is 'Relationship between Force, Work, and Acceleration Experiment'. An example analysis of this digital-related experiment is shown below.

Figure 2

Example Document Analysis for South Korea Physics Textbooks (Son et al., 2018)



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Research Results

South Korea

According to the analysis data, the distribution of digital-related experiments within physics textbooks of South Korea is shown in Table 5.

Table 5
Digital-related Experiment Distribution in the South Korean Physics Textbooks

Appliances	Percentage (%)
Video recorder	37
Digital calipers	9
Sound level meter	9
Virtual (simulation) experiment	9
Digital voltmeter	9
MBL	9
Geomagnetic sensor	9
Digital ammeter	9

Based on Table 5, the video recorder demonstrated the highest usage percentage at 37%, reflecting its predominant role among the digital tools utilized. This was followed by digital calipers, sound level meters, virtual (simulation) experiments, digital voltmeter and ammeter, MBL, and geomagnetic sensor, each accounting for 9% of usage.

United Kingdom

According to the analysis data, the distribution of digital-related experiments within physics textbooks of the United Kingdom is shown in Table 6.

Table 6
Digital-related Experiment Distribution in the United Kingdom Physics Textbooks

Appliances	Percentage (%)
Computer	34
Digital timer	22
Digital ammeters	11
Digital voltmeter	11
Oscilloscope	22

Based on Table 6, the computer showed the highest usage percentage at 34%, followed by other digital tools such as the digital timer and oscilloscope, each accounting for 22%. The digital voltmeter and ammeter contributed 11% to the overall usage.

Indonesia

According to the analysis data, the distribution of digital-related experiments within physics textbooks of the United Kingdom is shown in Table 7.

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Table 7
Digital-Related Experiment Distribution in the Indonesian Physics Textbooks

Appliances	Percentage (%)
Virtual (simulation) experiment	67
Smartphone	17
Multimeter	12
Oscilloscope	4

Based on Table 7, the virtual (simulation) experiment recorded the highest usage percentage at 68%, followed by other digital tools such as the smartphone (16%), multimeter (12%), and oscilloscope, which contributed only 4%.

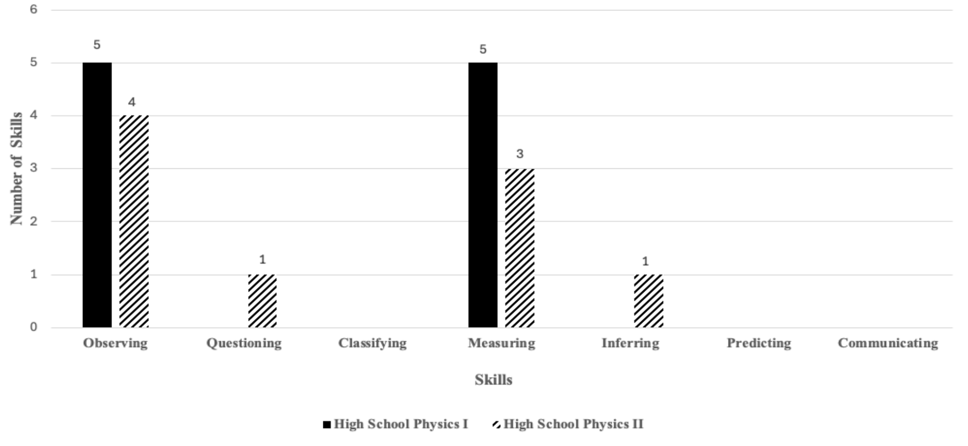
The Distribution of Basic Inquiry Skills in The Physics Textbooks

The distribution of basic inquiry skills in the physics textbooks from each country is shown below. This section highlights how these skills are integrated within the textbook's content.

South Korea

The distribution of basic inquiry skills in physics textbooks of South Korea is shown in Figure 3.

Figure 3
Distribution of Basic Inquiry Skills in the South Korean Physics Textbooks



According to Figure 3, which presents the distribution of basic inquiry skills in the physics textbooks of South Korea, the measuring and observing skills were the most prominent skills featured in Upper-secondary Physics I. In Upper-secondary Physics II, while measuring and observing skills remained present, the distribution of basic inquiry skills showed slight differences. Notably, two additional skills, questioning and inferring, were also incorporated.

United Kingdom

The distribution of basic inquiry skills in physics textbooks of the United Kingdom is shown in Figure 4.

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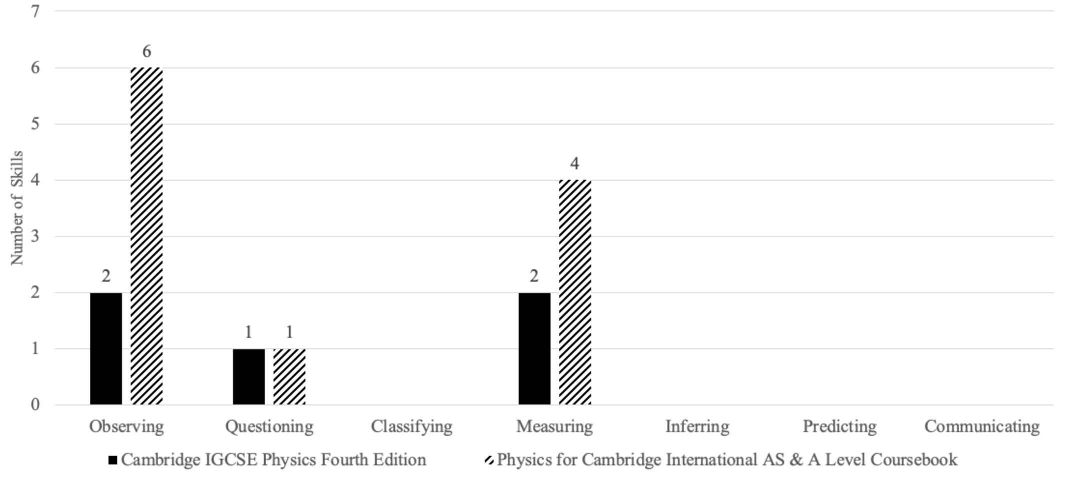
Figure 4
Distribution of basic inquiry skills in the United Kingdom physics textbooks

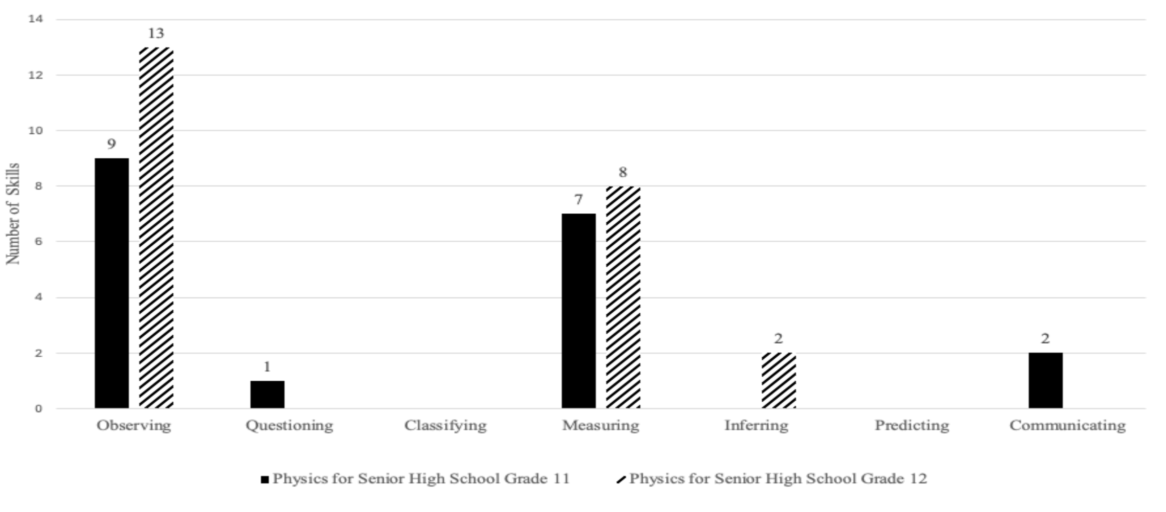


According to Figure 4, which presents the distribution of basic inquiry skills in the physics textbooks of the United Kingdom, the measuring and observing skills were the most prominent skills featured in Cambridge IGCSE Physics Fourth Edition. Physics for Cambridge International AS & A Level Coursebook, while measuring and observing skills remain present, the distribution of basic inquiry skills showed slight differences. Notably, one additional skill, questioning skills, was also incorporated into both textbooks.

Indonesia

According to the analysis data, the distribution of basic inquiry skills in the digital-related experiment within physics textbooks of Indonesia is shown in Figure 5.

Figure 5
Distribution of Basic Inquiry Skills in the Indonesian Physics Textbooks



According to Figure 5, which presents the distribution of basic inquiry skills in the physics textbooks of Indonesia, the measuring, observing, communicating, and questioning skills are featured in Physics for Upper-secondary Grade 11. Physics for Upper-secondary Grade 12, while measuring and observing skills remained pres-

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ent, the distribution of basic inquiry skills showed slight differences. Notably, one additional skill, inferring skills, was also incorporated.

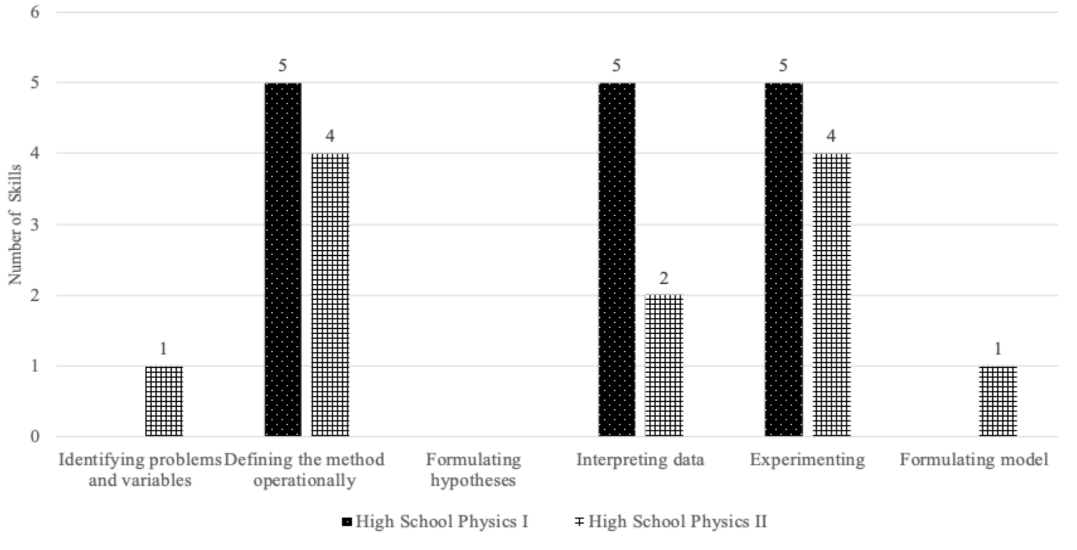
The Distribution of Integrated Science Process Skills in The Physics Textbooks

According to the analysis data, the distribution of integrated science process skills in the digital-related experiment within physics textbooks of each country is shown as follows.

South Korea

The distribution of integrated science process skills in physics textbooks of South Korea is shown in Figure 6.

Figure 6
Distribution of Integrated Science Process Skills in the South Korean Physics Textbooks



According to Figure 6, which presents the distribution of integrated science process skills in the physics textbooks of South Korea, defining operationally, interpreting data, and experimenting were the most prominent skills featured in Upper-secondary Physics I. In Upper-secondary Physics II, while defining operationally, interpreting data, and experimenting skills remained present, the distribution of integrated science process skills showed slight differences. Notably, two additional skills, identifying problems and variables, and formulating models, were also incorporated.

United Kingdom

The distribution of integrated science process skills in physics textbooks of the United Kingdom is shown in Figure 7.

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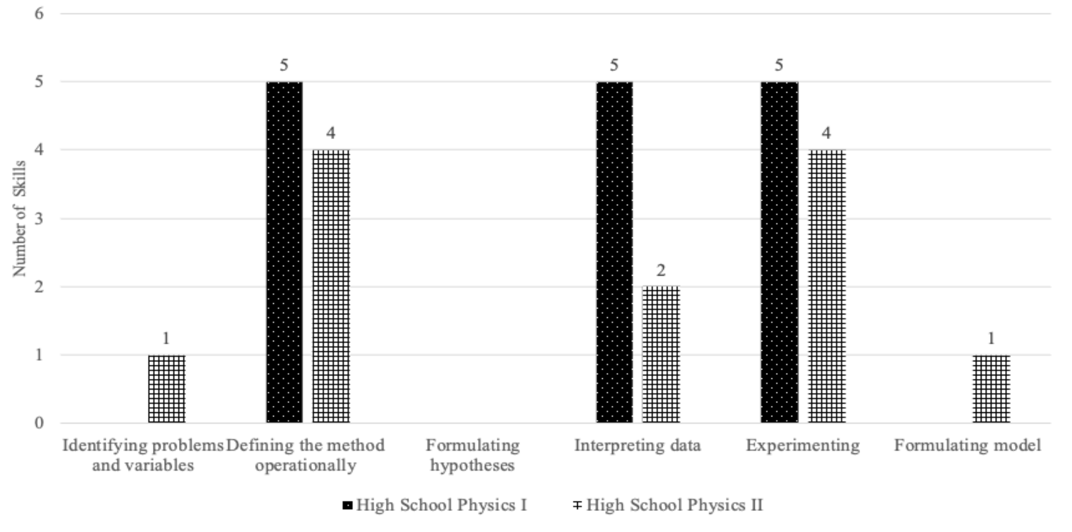
Figure 7
Distribution of Integrated Science Process Skills in the United Kingdom Physics Textbooks

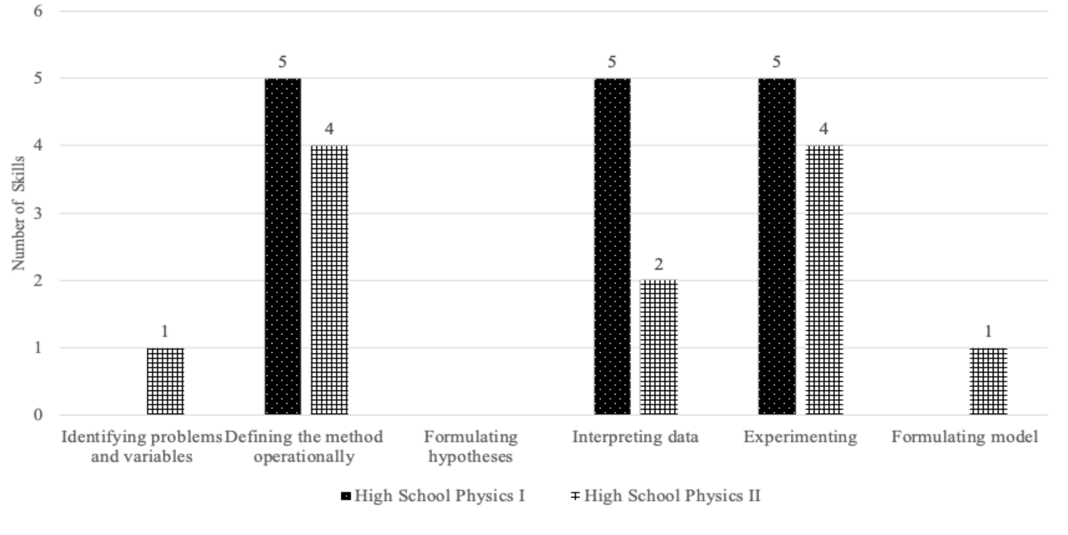


According to Figure 7, which presents the distribution of integrated science process skills in the physics textbooks of the United Kingdom, defining operationally, experimenting, and identifying problems and variable skills were the most prominent skills featured in the Cambridge IGCSE Physics Fourth Edition and Physics for Cambridge International AS & A Level Coursebook. Notably, only two skills, defining operationally and experimenting, were incorporated in Cambridge IGCSE Physics Fourth Edition.

Indonesia

According to the analysis data, the distribution of integrated science process skills in digital-related experiments within physics textbooks of Indonesia is shown in Figure 8.

Figure 8
Distribution of Integrated Science Process Skills in the United Kingdom Physics Textbooks



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According to Figure 8, which presents the distribution of integrated science process skills in the physics textbooks of Indonesia, the defining operational and experimenting skills were the most prominent featured in Physics for Upper-secondary Grade 11. In Physics for Upper-secondary Grade 12, while defining operational and experimenting skills remained present, the distribution of integrated science process skills shows various skills, including identifying problems and variables; interpreting data; and formulating models.

The distribution of basic inquiry skills and integrated science process skills in South Korea, the United Kingdom, and Indonesia is shown in Figures 9 and 10.

Basic Inquiry Skills

The distribution of basic inquiry skills in South Korea, the United Kingdom, and Indonesia is shown in Figure 9.

Figure 9
Distribution of Basic Inquiry Skills in South Korea, the United Kingdom, and Indonesia Physics Textbooks

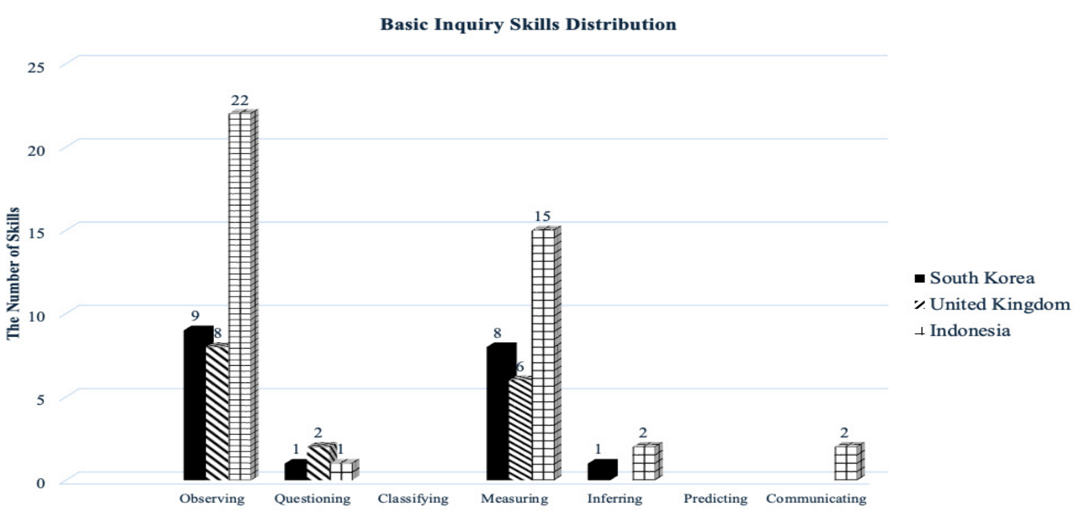

Figure 9 shows the distribution of basic inquiry skills in South Korea, the United Kingdom, and Indonesia. According to the data, the total number of all basic inquiry skills within physics textbooks of these three countries was 77 skills. The most prevalent basic inquiry skill found in digital-related experiments was observing. Observing skills reached the highest number of skills with a total of 39 instances identified across the three countries. Indonesia had the highest number with 22 observing skills, followed by South Korea with 9 skills, and the United Kingdom with 8 skills found in the physics textbooks. The second most frequently appearing skill was measuring, with a total of 29 skills across all three countries. Similarly, Indonesia led with 15 measuring skills, followed by South Korea with eight skills, and the United Kingdom with six skills. The third position was occupied by questioning skills, with a total of four skills across the three countries. The United Kingdom contributed two skills, while Indonesia and South Korea each contributed only one skill. Inferring skills were ranked fourth, with a total of three instances being identified exclusively in the textbooks from South Korea and Indonesia; no such skills were identified in the physics textbooks from the United Kingdom. The fifth position was communicating skills, with only two skills, both of which appear in Indonesian physics textbooks. Communicating skills were not found in the physics textbooks from South Korea or the United Kingdom. Lastly, classifying and predicting skills did not appear at all in the textbooks from any of the three countries.

Integrated Science Process Skills

The distribution of integrated science process skills in South Korea, the United Kingdom, and Indonesia is shown in Figure 10.

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Figure 10
Distribution of Integrated Science Process Skills in South Korea, the United Kingdom, and Indonesia Physics Textbooks

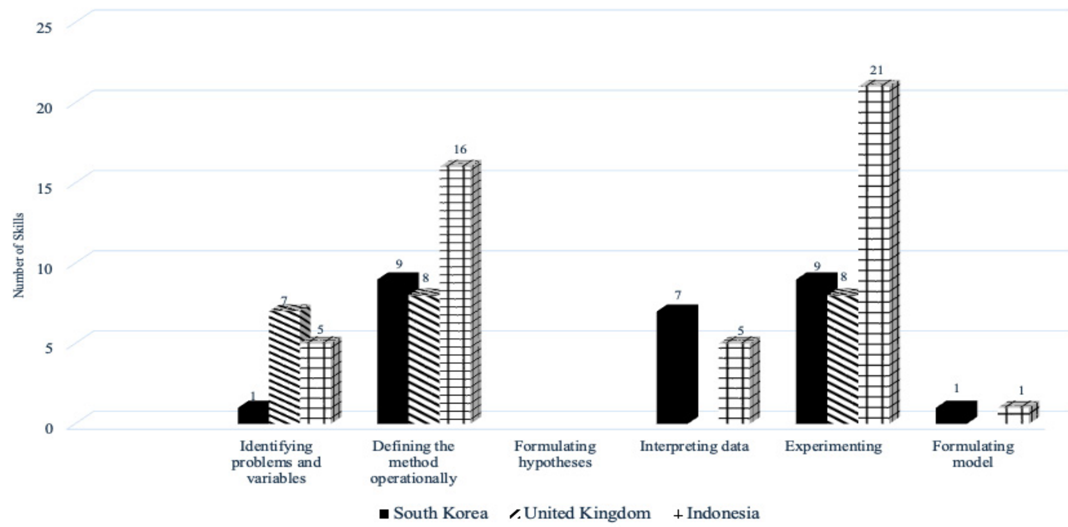

Figure 10 shows the distribution of integrated science process skills in South Korea, the United Kingdom, and Indonesia. According to the data, the total number of all integrated science process skills within physics textbooks of these three countries was 98 skills. The most frequently occurring integrated science process skill in digital-related experiments was experimenting. Experimenting skills reached the top skills, with a total of 38 skills identified across the three countries. Indonesia contributed the highest number with 21 experimenting skills, followed by South Korea with 9 skills, and the United Kingdom with 8 skills, as found in each physics textbook. The second most prevalent skill was defining the method operationally, with a total of 33 skills across the three countries. Indonesia reached with16 skills, followed by South Korea with 9 skills, and the United Kingdom with 8 skills. In third place was the skill of identifying problems and variables, which appears 13 skills in total. The United Kingdom contributed 7 skills, Indonesia had 5 skills, and South Korea had one skill. The fourth position was occupied by interpreting data, with 12 skills in total. Seven skills from South Korea and 5 from Indonesia, while this skill did not appear in textbooks from the United Kingdom. The fifth position was held by formulating models with only two skills in total, each from Indonesia and South Korea. These skills were not found in the United Kingdom physics textbooks. Lastly, the skill of formulating hypotheses did not appear at all in the physics textbooks from any of the three countries.

While Figures 9 and 10 highlight the frequency of basic inquiry and integrated science process skills in digital-related experiments, a deeper examination reveals differences in how these skills are embedded and scaffolded within the instructional design of each country's textbooks. In Indonesian textbooks, frequently appearing skills such as observing, measuring, and experimenting are often presented through direct, procedural instructions with limited progression in complexity. In contrast, South Korean textbooks, although lower in frequency, show signs of better scaffolding, particularly in skills such as interpreting data and defining methods operationally, where students are guided through increasingly complex tasks. UK textbooks, while featuring fewer total skill instances, often integrate skills such as questioning and identifying variables within contextualized, inquiry-based learning activities. This approach indicates a stronger alignment with scientific reasoning. However, across all three countries, the absence of certain higher-order skills, such as formulating hypotheses or predicting, and the limited use of communication and modeling, suggest a gap in the comprehensive development of scientific inquiry.

Discussion

According to the results, the utilization of digital-related experiments in these physics textbooks in each country aligns with the goal of Science-Technology-Society (STS) education. In South Korean physics textbooks, the most digital-related experiment that is used is a video recorder. The remaining digital tools are used, including digital calipers, sound level meter, virtual (simulation) experiment, digital voltmeter, MBL, and geomagnetic sensor. Moreover, in the United Kingdom, the most digital-related experiment used in physics textbooks is a computer. The

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remaining digital tools are used, including digital timers, oscilloscopes, digital voltmeters, and digital ammeters. Furthermore, in Indonesian physics textbooks, the most digital-related experiment that is used is a virtual (simulation) experiment. The remaining digital tools are used, including a smartphone, multimeter, and oscilloscope. The implementation of digital-related experiments in each country appears to be influenced by the availability of educational tools and resources. In South Korea, the digital-related experiment that was dominant was the video recorders, which assist students in collecting precise measurement data during experiment activities. At the same time, hands-on experiments were also presented. Similarly, in the United Kingdom, the computer device was dominantly utilized to support long-duration experiments, which also supports the accuracy of data analysis. The balanced integration of digital-related and hands-on experiments observed in South Korea and the United Kingdom may reflect a more comprehensive approach to experimental science education. Such an approach can play a critical role in fostering students' scientific inquiry skills and conceptual understanding. In contrast, in Indonesia, limited access to physical experiment tools has resulted in an overreliance on virtual simulations. This lack of diverse experimental opportunities may have constrained the development of students' science process skills and limited their engagement in inquiry-based learning. Nevertheless, both South Korea and the United Kingdom present high-quality hands-on experiments, which result in the limited utilization of digital-related experiment tools. In contrast, Indonesia displays many virtual simulations because of the limited physical laboratory tools. This suggests that digital-related experiments in Indonesia were complementary tools to guide the student in the learning process, as a consequence of the absence of comprehensive hands-on experimental equipment. Hodson (2020) has argued that the goal of STS education is to see the students utilize technology as real-world experiences and increase awareness of an issue that aims to improve science learning. Gardner (1999) has also argued that the decisions or ideas that students form regarding science and technology, as well as their relationship, affect their decision-making for their future lives and careers, or determine their expertise in their future education. Walan (2020) has declared that digital technology helps the teacher visualize abstract scientific phenomena and engage students in a meaningful study. Chen (2017) has found that digitized textbooks affected student engagement, including the senses of vision and touch in science learning.

The distribution of basic inquiry skills in the digital-related elements of physics textbooks from South Korea, the United Kingdom, and Indonesia predominantly emphasizes observing and measuring skills, while other skills are only minimally incorporated. The need for integrating basic inquiry skills into digital-related experiments and incorporating a broader range of such skills is necessary. The distribution of basic inquiry skills in digital-related experiments in physics textbooks from South Korea, the United Kingdom, and Indonesia, which are incorporated within the textbooks, mostly involves observing skills. Measuring skills also became the second prevalent skill, followed by questioning skills. In the case of inferring and communicating skills, only one to two countries are provided within their textbooks. In contrast, the skills of classifying and predicting skills were not provided in the physics textbooks of three countries. Jong et al. (2013) have argued that the combination of virtual and physical design, with a well-designed, assists students in obtaining a more complex understanding of scientific phenomena and developing inquiry skills. Ješková et al. (2018) have explained that in the process of learning science, particularly physics, students should gain not only scientific knowledge but also skills to inquire to understand how scientists work. Wang et al. (2015) have found that model-based inquiry in physics virtual lab pedagogy, introducing the virtual experiment design and analysis, can give a deep practice of science process skills, comprehensive and reflection skills of scientific inquiry.

The distribution of integrated science process skills in digital-related experiments from South Korea, the United Kingdom, and Indonesia that are incorporated within the physics textbooks are mostly experimenting skills, while the other skills are only minimally incorporated. Embedding integrated science process skills in digital-related experiments within physics textbooks is essential. Defining the method operationally skills also become the second prevalent skill, followed by identifying problems and variables. In the case of interpreting data dan formulating models, only two countries provided the skills within physics textbooks. In contrast, the formulating hypotheses skill was not provided within the physics textbooks of the three countries. Kuriniawati (2021) has stated that science process skills, which covered basic and integrated process skills, were closely related to science learning. Saat (2004) has found that the analysis of children's cognitive behaviors provides some insight concerning cognitive skills instruction and the integrated science process skills acquisition in the web-based learning environment. This supports the notion that the integrated science process skills in digital-related experiments contribute to the development of students' cognitive skills. El-Sabagh (2011) has found that web-based virtual labs provided considerable support for students and helped them to improve their conceptual understanding of science and science process skills.

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Conclusions and Implications

This study analyzed and compared the distribution of digital-related experiments, basic inquiry skills, and integrated science process skills within upper-secondary physics textbooks in South Korea, the United Kingdom, and Indonesia. The purpose of this study is to analyze and compare the basic inquiry and integrated science process skills in digital-related experiments within physics textbooks of South Korea, the United Kingdom, and Indonesia.

The results obtained from the distribution of digital-related experiments in South Korean physics textbooks show that the most commonly used digital-related experiment is a video recorder. In the United Kingdom, in physics textbooks, the most digital-related experiment that is used is a computer. In Indonesian physics textbooks, the most digital-related experiment that is used is a virtual (simulation) experiment. Moreover, the distribution of basic inquiry skills in the digital-related elements of physics textbooks from South Korea, the United Kingdom, and Indonesia predominantly emphasizes observing and measuring skills, while other skills are only minimally incorporated. Each country has quite a different distribution of basic inquiry skills. However, the classifying and predicting were not found in any textbooks. Furthermore, the distribution of integrated science process skills in digital-related experiments from South Korea, the United Kingdom, and Indonesia, which are incorporated into the physics textbooks, are mostly experimenting skills, while the other skills are only minimally incorporated. The integrated science process skills are distributed differently across these countries. However, formulating hypotheses was not found in any textbooks.

This study strongly emphasizes the digital-based experiments, which highlight the optimization of basic inquiry and integrated science process skills distribution. These science process skills are not only used during hands-on experiments but also when using digital-related experiments. Although modern technological tools are embedded in physics textbooks to enhance learning effectiveness, it is essential that their use also promotes the balanced development and assessment of all science process skills at the upper-secondary level. According to Piaget's theory of cognitive development, upper-secondary students are generally in the formal operational stage, a phase characterized by the ability to think abstractly, reason logically, and engage in systematic problem-solving. At this developmental stage, students are not only capable of learning and applying basic inquiry skills but are also developmentally prepared to engage with more complex, integrated science process skills. The materials provided at the upper-secondary level generally foster the foundational and advanced scientific process, thinking, and skills. These abilities are essential for engaging students in scientific inquiry and understanding. The results of this study show that most digital-related experiments focused on observing and measuring skills within the experiments, without formulating hypotheses based on the digital tools used. For example, in South Korean physics textbooks, the most used digital-related experiment involves using a video recorder to record the motion of a wooden block. In United Kingdom physics textbooks, the most used digital-related experiment involves connecting a computer to a motion sensor as an alternative to a stopwatch to measure the period of a pendulum. In Indonesian physics textbooks, the most used digital-related experiment is a virtual (simulation) experiment used to determine the magnitude of the Coulomb force. Most of these tools were used because they are effective for observation and data collection, but they are less effective in fostering the formulation of hypotheses. For instance, one potential improvement could be to provide a guide on the utilization of digital tools, outlining how predictions or hypotheses could be formed based on the expected outcomes in experiments when using digital-related tools.

Furthermore, this study can be used as a reference in developing educational policy or curriculum on a global scale. It provided insight into how different countries and cultures embedded digital-related experiments in their physics textbooks at the upper-secondary level. This research can give information to the policymakers and curriculum developers about what type or trend is the best to improve the digital-related experiment implementation. It encourages the authorities of the education field to update or improve the integration of digital technology within textbooks, curricula, or educational policy. While some general implications, such as the importance of aligning textbook content with science process skills, can be applied broadly, specific implementation strategies may vary across countries due to differences in curriculum standards, teacher training systems, and digital infrastructure. An effective starting point for implementation could be professional development programs that train teachers to identify and integrate science process skills into digital-related experiments. Additionally, textbook developers could be guided to align activities more explicitly with the national learning objectives of each country. Some science process skills may be more effectively taught through specific topics. For example, 'hypothesis formulation' may be better integrated in inquiry-based electricity experiments, while 'data interpretation' may be stronger in topics like motion and forces. This is an area worth exploring further and could form the basis for future analysis.

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Declaration of Interest

The authors declare no competing interest.

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DEVELOPMENT OF AN ARTIFICIAL INTELLIGENCE-SUPPORTED CHATBOT AS AN INTERACTIVE LEARNING PLATFORM IN STEM EDUCATION: EXPLORING USABILITY AND STUDENT EXPERIENCE

Gábor Fekets

Abstract. *While generative artificial intelligence (AI) tools are gradually being integrated into educational practice, their actual usability in classroom settings remains insufficiently understood. This mixed-methods research was designed as a small-sample pilot study, offering preliminary insights to inform a future large-scale scientific evaluation. The following questions were explored: What are the contents, functions, and capabilities of AI-based chatbots in education? How do students evaluate the usability of a chatbot using BUS-15 metrics? The online developer system botpress.com was chosen as the framework to support physics education within STEM fields for upper-secondary students. A validated instrument, BUS-15, a commercial tool for measuring chatbot usability, was utilised in an educational setting to evaluate students' user experience. In May 2025, 37 Taiwanese students used the developed AI chatbot. Cronbach's a was 0.709, consistent with values typically observed for chatbots developed for business purposes. Based on the results, the chatbot met the students' expectations. Accessibility emerged as a key determinant of chatbot success, although issues were noted with response times and conversational coherence. The findings also underscore the importance of evaluating a chatbot's pedagogical value, specifically its potential to enhance learning experiences and support multilingual engagement.*

Keywords: *AI chatbot, BOT Usability Scale, Botpress in education, BUS-15 questionnaire, interactive learning platform*

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Introduction

The global COVID-19 pandemic accelerated demand in the educational sector for technologies that facilitate online learning. Artificial intelligence (AI) chatbots have emerged as one of the most widely adopted tools in this context (Okonkwo & Ade-Ibijola, 2021). These AI-driven applications support student learning by providing personalised instruction and real-time feedback, reducing the administrative burden (Bettayeb et al., 2024; Mishra & Varshney, 2024). Additional advantages include around-the-clock accessibility and human-like conversational interaction, both of which contribute to a more seamless educational experience (Ghayoomi, 2023). Research has also shown that AI chatbots enhance student motivation, engagement, and satisfaction in STEM education by improving service quality and delivering tailored support, factors that ultimately contribute to improved student retention (Neji et al., 2023; Segovia-García, 2024).

Previous studies have highlighted the pivotal role of ChatGPT in AI-supported learning pathways, with particular success in personalised instruction and real-time assessments in mathematics education (Opesemowo & Adewuyi, 2024). Performance expectations strongly influence users' intended outcomes, which in turn affect continued use of ChatGPT (Bazelais et al., 2024). Saxena and Doleck (2023) reported rapid acceptance of the platform, reinforcing the need to understand the factors driving user intention and sustained engagement. Wardat et al. (2023) examined the integration of ChatGPT into mathematics teaching, confirming its positive impact on student success through comprehensive guidance and instructional support. In broader STEM education, chatbots have demonstrated the ability to enhance student confidence and learning outcomes by delivering timely, adaptive assistance (Luzano, 2024). Their effectiveness is particularly evident in science instruction, where they outperform traditional rule-based systems in fostering active learner participation (Ng et al., 2024).

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A recent scoping review examined students' perceptions of AI chatbots in higher education, emphasising their motivational benefits and overall usefulness, while also raising concerns related to response accuracy and potential negative effects on learning (Schei et al., 2024). Notably, researchers have cautioned against diminished creativity and critical thinking skills, suggesting the need for further analysis of the broader cognitive impacts of chatbots (Hasan et al., 2024). Some concerns suggest that increased reliance on chatbot-generated responses may erode the role of human instructors and the teacher–student dynamic, with some studies noting potential emotional attachment to AI systems. A key research gap lies in the limited availability of locally relevant knowledge bases, which can undermine the accuracy and contextual relevance of chatbot responses. Addressing this limitation is essential for improving both the effectiveness and adaptability of AI chatbots in educational settings (El Azhari et al., 2023).

At the same time, the integration of AI-supported tools in education brings ethical and legal challenges, particularly regarding data privacy and the preservation of meaningful human interaction in the learning process (Hasan et al., 2024; Schei et al., 2024). Rule-based chatbots have become less effective due to the rapid advancement of computer performance and natural language processing (NLP). The revolution in AI and generative models has significantly enhanced the conversational capabilities of chatbots and their ability to provide complex responses.

Research Problem

This research addresses the following three challenges. First, student disengagement in physics, which is often viewed as complex and uninspiring, can negatively impact academic performance and diminish enthusiasm for future engagement in STEM fields. Second, the study introduces an AI-based chatbot specifically designed to foster engagement and evaluate user experience through statistical methods. By leveraging interactive features and personalised support, the chatbot aims to create a more stimulating and accessible learning environment. This innovative approach is intended to boost student interest in physics, deepen conceptual understanding, and cultivate a more positive attitude toward STEM education. Third, despite the rich theoretical landscape surrounding chatbot development, no commercial instruments have yet been employed to assess user experience within educational settings. The PARADISE framework (Walker et al., 1997) supports performance measurement in spoken dialogue systems, offering a comprehensive tool for evaluating conversational accessibility, functionality, interaction quality, reliability, and user trust. While usability tools such as Usability Metric for User Experience (Finstad, 2010) are commonly used to gauge system and interface usability, they do not explicitly address chatbot-specific characteristics. Valério et al. (2018) also emphasised the absence of instruments that capture end-user experience in chatbot interactions. As chatbot applications grow within commercial domains, the need to evaluate their qualitative performance has become increasingly urgent (Federici et al., 2020). Responding to this gap, Borsci et al. (2022) developed the BOT Usability Scale (BUS-15), a 15-item questionnaire with demonstrated reliability ranging from .76 to .87, designed to assess user satisfaction with AI conversational agents.

To the best of my knowledge, no previous studies have implemented a customised AI chatbot while measuring user experience in the educational domain. Several research gaps remain: for example, no studies have assessed tools or development methods for implementing customised educational chatbots; chatbots are typically deployed as standalone tools rather than integrated systems, and no studies have used AI to assess student performance. Additionally, no generalised model currently exists to define essential chatbot functions and services, and standardised usability instruments and statistical methods for evaluating educational chatbot interactions remain absent.

To address these gaps and advance research in this domain, a customised AI-based chatbot was developed using the botpress.com developer platform, and its user experience was evaluated using standardised quantitative instruments.

Research Focus

As generative AI tools have become increasingly affordable and accessible, questions have emerged regarding their practical application and effectiveness within the education sector. This research addresses the following key areas. First, a review of the state of the art in AI chatbot technologies is conducted. Second, the application of chatbots in educational contexts is explored. Third, an integrated chatbot platform is described, detailing its functions, data structures, and defined user roles and tasks for students, teachers, and parents. Finally, the platform is evaluated in terms of its usability in upper-secondary education.

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Research Aim and Research Questions

First, a new AI-based chatbot tool using the botpress.com development framework is presented. Then, its usability is assessed based on students' user experiences, with a focus on exploring how AI-driven chatbots can support students in STEM education. Two research questions are posed: What content and functions should AI-driven chatbots offer to support students in STEM education? Do students find such chatbots useful?

Research Methodology

General Background

The continued development of AI has opened new possibilities for personalised learning. Chatbots serve as interactive tools that enhance student engagement and support efficient knowledge retrieval. This study developed a customised AI chatbot and tested its usability and student satisfaction in a physics course for upper-secondary students. Numerous recent studies have explored the use and impact of chatbots in education. However, the user experience remains underexplored, with most research focusing solely on student satisfaction, rather than usability, interaction quality, or pedagogical impact. The System Usability Scale (Brooke, 1996) is a general usability questionnaire that is applicable to chatbots. The BUS-15 instrument evaluates commercial chatbot usability; it has not been applied in educational contexts. To address this gap, mixed-methods research was conducted to evaluate the developed customised educational chatbot.

Participants

We recruited 37 upper-secondary school students aged 15–16 years (19 males, 18 females), randomly selected from one secondary school in Taiwan. The test was anonymous, and no personal data were collected. Participants volunteered during a scheduled IT lesson, using the school's internet and Chromebooks. The 90-minute session included three phases: a 20-minute introduction to the study goals, a 50-minute hands-on exploration of the chatbot's main functions via guided learning materials, and a 20-minute paper-based BUS 15 questionnaire. The study did not require a control group; thus, all students experienced the same condition, and informed consent was obtained beforehand. Demographic data, including age, sex, prior generative AI experience, and usage frequency, were recorded to contextualise the findings. With 37 participants, the sample size was sufficient to reveal key usability issues, considering that major problems typically surface within the first few dozen users (Faulkner, 2003).

Instrument and Procedures

The AI chatbot was developed using Botpress Cloud Studio (build 2024-11-19) on an Ubuntu 22.04 LTS desktop computer equipped with an Intel i7-7700 CPU and 32 GB RAM. Intent recognition was handled by the platform's continuously updated generative NLU model, eliminating the need for manual retraining. The system is automatically upgraded with the latest examples. Five primary flows (Login, Teacher's task, Parent's access, Student area, Questionnaire) were implemented, creating a total of 74 nodes. Each AI node ran the GPT-4o-Mini language model (August 2024 release), configured to produce responses that balanced creativity and consistency (a "temperature setting" of 0.6). The platform integrated the OpenAI-Botpress API (version 15.0.1), enabling cloud-based development. To evaluate the tool's usability and effectiveness, the BUS-15 questionnaire was employed. This standardised instrument offers a systematic framework for assessing user experience based on key dimensions: ease of use, efficiency, and satisfaction. Responses were measured using a Likert scale to capture nuanced perceptions of students' interactions with the chatbot. The questionnaire consists of 15 concise, age-appropriate items suitable for 15–16-year-old students, with a format brief enough to maintain engagement during a classroom activity.

A distinctive aspect of this study is the application of a commercial usability instrument within an educational context. The BUS-15 provides a structured methodology that ensures consistent measurement across different chatbot systems. Moreover, it addresses both functional and emotional aspects of user experience, offering a comprehensive view of student–AI interaction. Table 1 outlines the structure of the instrument.

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Table 1
BUS 15 Questionnaire

Factor	Item
1 - Perceived accessibility to chatbot functions	1. The chatbot function was easily detectable. 2. It was easy to find the chatbot.
2 - Perceived quality of chatbot functions	3. Communicating with the chatbot was clear. 4. I was immediately made aware of what information the chatbot could give me. 5. The interaction with the chatbot felt like an ongoing conversation. 6. The chatbot was able to keep track of context. 7. The chatbot was able to make references to a website or service when appropriate. 8. The chatbot could handle situations in which the line of conversation was not clear. 9. The chatbot's responses were easy to understand.
3 - Perceived quality of conversation and information provided	10. I found that the chatbot understood what I wanted and helped me to achieve my goal. 11. The chatbot gave me the appropriate amount of information. 12. The chatbot only gave me the information I needed. 13. I felt that the chatbot's responses were accurate.
4 - Perceived privacy and security	14. I think that the chatbot informed me of any possible privacy issues.
5 - Time response	15. The response time was short.

Source: Borsci et al. (2020)

Data Analysis

Findings from the BUS-15 questionnaire were systematically analysed to determine the internal consistency of the instrument in the context of an educational chatbot. I examined recurring themes in open-ended responses and statistically assessed Likert-scale ratings. Patterns in user feedback informed recommendations for system improvements and enhancements to the overall user experience. This dual-method approach enabled the identification of both strengths and weaknesses in the chatbot interactions. By integrating quantitative and qualitative data, I ensured a balanced evaluation that captured a diverse range of student perspectives. The BUS-15 remains a reliable instrument for assessing chatbot usability and guiding future developments. In this pilot study, the questionnaire functioned solely as a data-collection tool. No psychometric validation procedures (e.g., factor analysis or item-level diagnostics) were conducted, as scale development was not the primary objective. Descriptive statistical analysis was used to summarise and explore the distribution of student responses. This analysis facilitated a broad understanding of user sentiment and general trends, while helping to identify areas for potential improvement. Internal consistency metrics were calculated (Cronbach, 1951). Item-total correlation was excluded, as the aim was exploratory rather than diagnostic. Cronbach's alpha was deemed appropriate given that the BUS-15 is in English, while students' primary language is Traditional Chinese. This allowed an assessment of response consistency, cultural adaptation, and potential language barriers. Responses were processed using Python, selected for its simplicity, robust statistical libraries (e.g., Pandas, NumPy), and cross-platform compatibility. The anonymised dataset containing student responses is available via Zenodo (Fekets, 2025), thereby supporting transparency and reproducibility in future analyses. Finally, to explore deeper patterns and insights from the BUS-15 data, students were asked to respond to open-ended questions at the conclusion of the instrument. Table 2 presents the structure of this inquiry.

Table 2
Open-Ended Questions

Factor	Related question
Accessibility	How easy or difficult was it to start using the chatbot?
Function quality	How fun and interesting were the chatbot's tasks?
Conversation quality	How natural or robotic were the chats?
Privacy and security	Did you feel safe and comfortable using the chatbot?
Time response	How fast did the chatbot respond to you?

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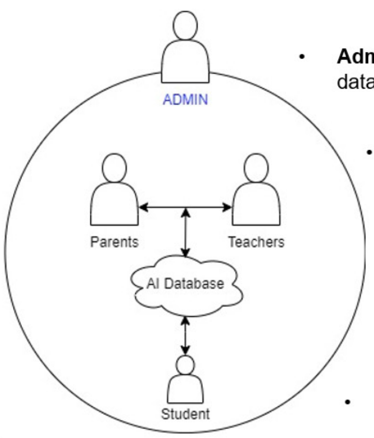
The open-ended responses were not analysed in depth, as the focus of the study was on quantitative usability trends derived from the Likert-scale items.

Research Results

To address the research questions, an AI chatbot was developed using the Agile methodology (Beck et al., 2001), tailored to support physics-focused STEM education. The system includes distinct modes for students, teachers, and parents, with access permissions and functionalities assigned according to predefined user privileges (see Figure 1). From Figure 2 to Figure 8, the developed menu and function list are presented.

Figure 1
Roles of Teachers, Parents, Students, and Admin



- **Admin user:** maintains, updates, and backs up the code. 2nd level user management, data analysis, content management, system-related notification management.
- **Teachers:** develop content, generate ideas, 1st level user maintenance, send messages and use the calendar function for administrative tasks. Class management, student engagement, performance tracking, parental communication.
- **Parents:** Monitoring academic progress, attendance tracking, engagement with teachers, and resource access.
- **Students:** study resources, task and project submission, performance feedback.

Figure 2
After Logging In, Students Can Select the Type of Activity Within the Task-Selection Interface.

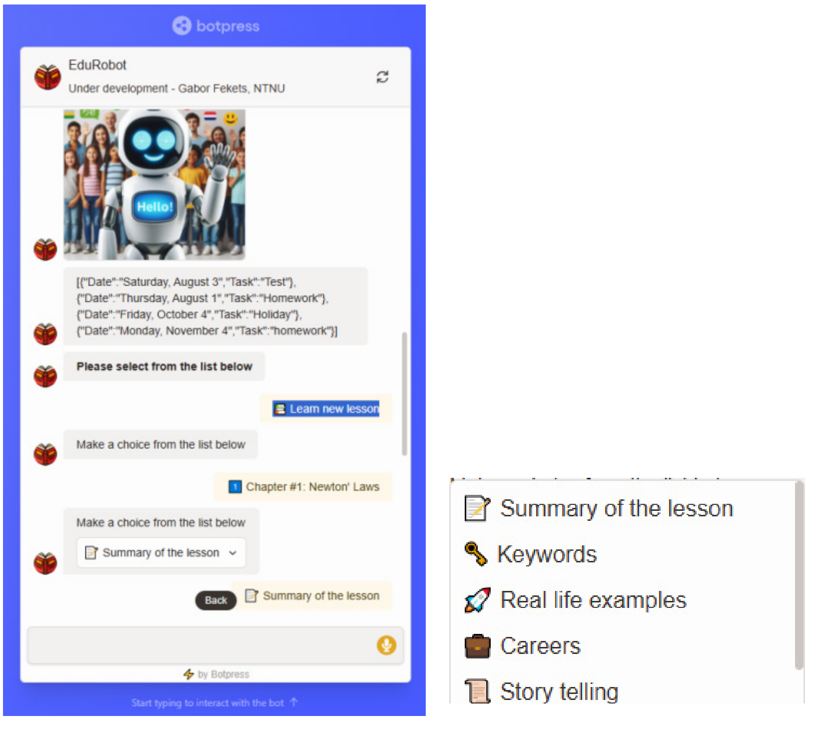


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Figure 3

The Lesson Summary Panel Displays a Brief Overview of the Session's Key Points.

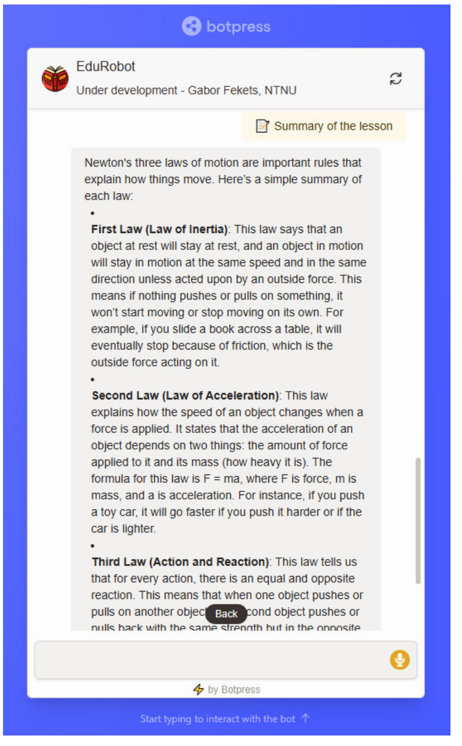
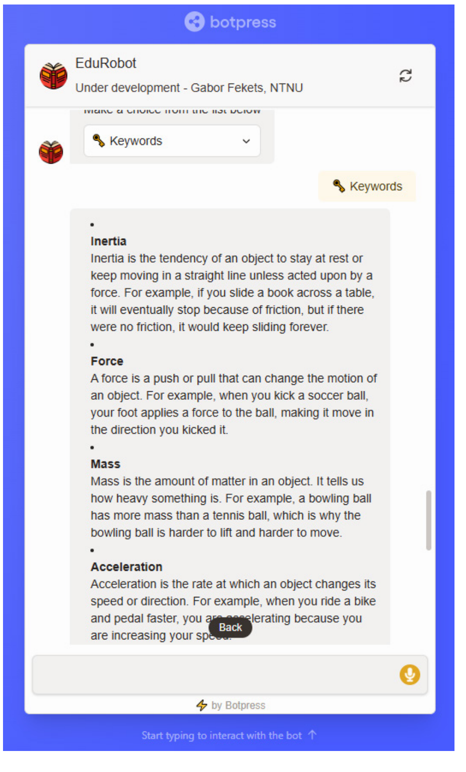


Figure 4

AI-Generated Content Produced by the Keywords Function, Illustrating Automated Keyword-Based Summarisation.



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The "Storytelling" session was generated by the AI system and presented a short narrative based on Newton's Law. After reading the story, students responded to questions designed to reinforce comprehension and retention of key concepts.

Figure 5
AI-Generated Storytelling Task Based on Newton's Law

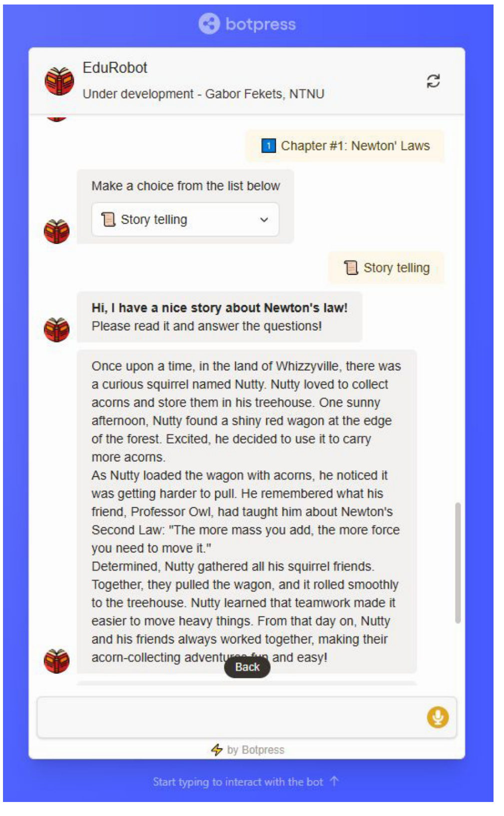

Figure 6 presents the comprehension questions based on the short story, while Figure 8 displays the scoring interface, providing immediate feedback on student responses. The underlying code also generated scores and tracked students' performance on the selected topic.

Figure 6
Storytelling Questions Generated by the AI System

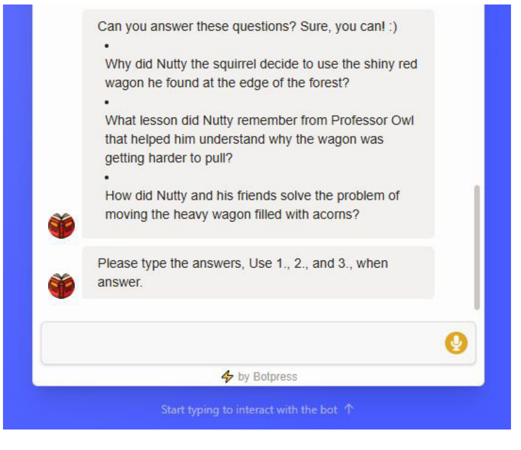

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Figure 7
AI-Generated Scoring and Feedback Based on Student Responses

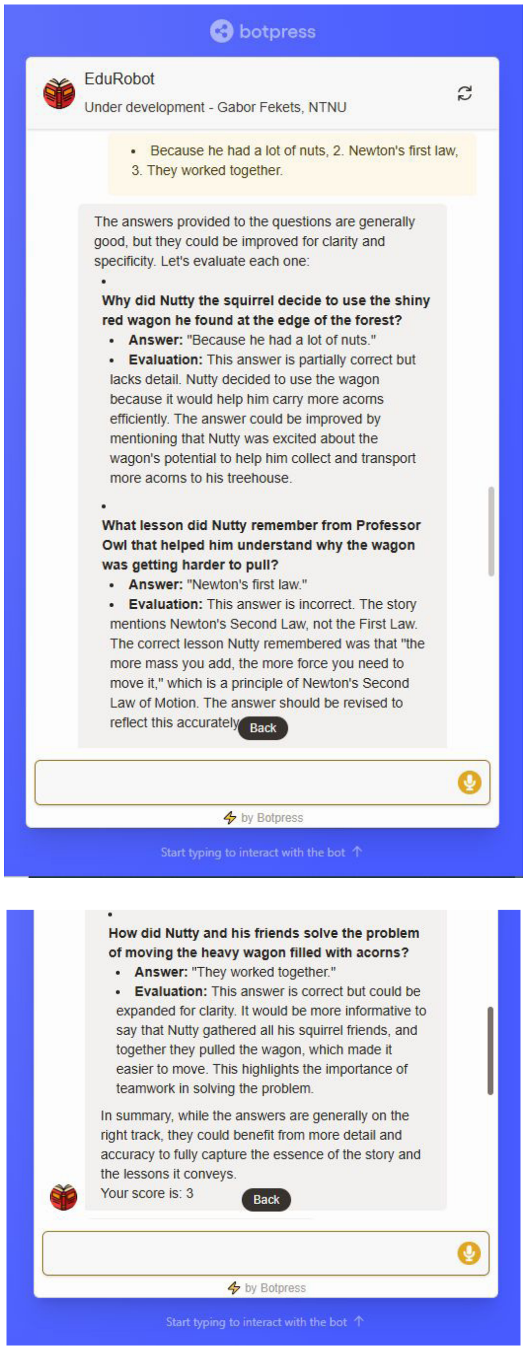

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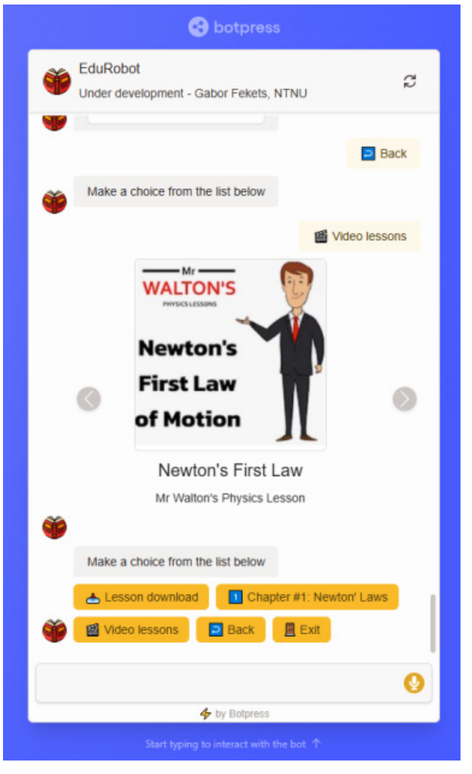
Figure 8
Integration Feature Allowing Teachers to Embed YouTube Videos as Visual Content Within the Lesson Interface.



Qualitative and Quantitative Results

Descriptive statistics were computed for all questionnaire items to examine central tendency, variability, and distributional properties of the responses. The number of valid observations (*n*) varied slightly across items due to a small number of missing entries, ranging from 36 to 37 responses per item. Table 3 reports the calculated means, standard deviations, minimum and maximum scores, along with skewness and kurtosis coefficients for each item.

Table 3
Descriptive Statistics for Questionnaire Items

Item	*n*	*M*	*SD*	Min	Max	Skewness	Kurtosis
Q1	36	3.25	1.13	1	5	-0.02	-0.71
Q2	37	3.38	1.06	1	5	-0.52	-0.41
Q3	37	3.57	1.07	1	5	-0.32	-0.61
Q4	37	3.05	0.91	1	5	0.12	-0.32
Q5	37	2.73	1.1	1	5	-0.09	-0.9
Q6	37	2.35	1.27	1	5	0.62	-0.63
Q7	36	3.25	1.05	1	5	-0.51	-0.15
Q8	37	3.35	0.82	2	5	0.18	-0.45
Q9	37	2.62	1.06	1	5	-0.04	-0.69

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Item	*n*	*M*	*SD*	Min	Max	Skewness	Kurtosis
Q10	37	2.14	0.92	1	4	0.17	-1.02
Q11	37	3.16	1.01	1	5	-0.17	-0.41
Q12	37	2.51	1.1	1	5	0.16	-0.81
Q13	37	3.08	1.23	1	5	-0.16	-0.83
Q14	36	3.31	1.14	1	5	-0.15	-0.78
Q15	36	2.78	0.93	1	5	0.24	-0.45

Mean scores ranged from 2.73 (Q5) to 3.57 (Q3), reflecting moderate levels of agreement or endorsement depending on the content of each item. Standard deviations fell between 0.82 and 1.27, indicating acceptable variability in participants' responses. Skewness values ranged from −0.52 to +0.12, implying near-symmetric distributions with a slight leftward skew in some items. All kurtosis values were negative (−0.90 to −0.32), indicating platykurtic distributions with fewer extreme observations than expected under normality. Collectively, these metrics support the assumption of approximate normality, permitting the use of parametric analysis techniques. To evaluate internal reliability, Cronbach's alpha was calculated using complete responses only (i.e., excluding cases with missing data). The resulting coefficient was 0.709, representing acceptable internal consistency. This implies that the questionnaire items collectively measure a coherent construct, although some scope for refinement or item-level optimisation may remain. Overall, the descriptive results reveal balanced and varied student responses. The internal consistency of the instrument further supports its use for inferential analysis and scale-based interpretation. Table 4 summarises the average factor scores derived from the questionnaire.

Table 4
Average Scores for Each Factor

Factor	Number of items	*M*	*SD*	Evaluation
Accessibility	2	3.34	1.09	Strength
Function quality	7	2.99	1.05	Moderate performance
Conversation quality	4	2.72	1.04	Weak point
Privacy and security	1	3.31	1.14	Strength
Time response	1	2.78	0.93	Weak point

Across all questionnaire items, four missing responses were observed. Analyses were conducted using all available data for each item (pairwise inclusion), while reliability assessments were restricted to complete cases (listwise deletion, $n = 33$). Participants also responded to five open-ended questions aimed at exploring their subjective experiences with the autonomous conversational agent. These qualitative responses were not analysed using formal metrics but were employed as illustrative examples to contextualise the quantitative results. Students found accessing the chatbot (M = 3.34) via QR code intuitive, particularly on Chromebook devices. Typical comments included, "Using the QR code and entering the bot was easy," and "I also use QR codes on my phone frequently; it's easy." Function quality received a mean score of 2.99. Some students stated, "The bot's activities were useful, but I wish there were more of them," and "It is easier to learn with this bot." Conversation quality recorded the lowest average score (M = 2.72), with students frequently noting the challenge of navigating English-language content. Representative comments included, "My English is not so good; I read all of the sentences three or four times," and "I don't like typing too much, tapping is easier." Privacy and security (M = 3.31) did not raise concerns. Students completed the login process appropriately and did not report the collection of personal data. In one instance, a student attempted to access another account, but the system's use of unique credentials prevented unauthorised access. Response time (M = 2.78) was the second-lowest-rated factor. For students unfamiliar with chatbot interactions, delays in response attributed to AI processing requirements were occasionally noted. Some system messages also contributed to wait times, potentially stemming from backend limitations. In summary, these insights

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contextualise the BUS-15 scores, reveal practical limitations, and offer guidance for refining chatbot functionality to enhance the user experience in future educational applications.

Discussion

With the rapid evolution of information technology, the adoption of AI tools in education is both inevitable and increasingly essential for enhancing traditional instructional practices. Among these tools, chatbots, an especially promising application of generative AI, have demonstrated considerable potential to foster student engagement in STEM disciplines. Mai et al. (2024) identified several limitations and threats associated with ChatGPT through a SWOT analysis. One notable limitation of general-purpose AI systems lies in their broad, non-specialised instructional outputs. The present study addressed this concern by designing a subject-focused chatbot tailored to physics education. Furthermore, the bot can be adapted across diverse subjects.

Previous research has highlighted additional limitations, including excessive response length (Chaudhry et al., 2023), content complexity (Stojanov, 2023), and minimal motivational impact on students facing challenging tasks (Yilmaz & Karaoglan Yilmaz, 2023). To counter these issues, the developed chatbot integrated a performance-based reward system, allowing students to earn points for their responses. This feature is designed to increase short-term engagement and promote task completion.

Concerns regarding diminished critical thinking, raised by Mohamed (2024) and Sallam et al. (2023), are particularly relevant in STEM education, where analytical reasoning forms a core component of curriculum goals. To foster such skills, the chatbot incorporates interactive questioning and contextualised real-life examples that encourage deeper cognitive engagement with physics concepts.

Despite its strengths, the chatbot cannot replicate the experiential learning and innovation essential to applied sciences education. While capable of supporting concept acquisition and foundational understanding, it does not substitute for hands-on experimentation or the nuanced communicative presence of a live teacher, including non-verbal cues and tone. As such, the chatbot should be considered a supplementary tool, a knowledge-rich, interactive support system, but not a standalone teaching solution.

An important achievement of this project was the use of the Botpress framework's Personality Agent, which delivers differentiated responses based on user age and prior knowledge. This feature enhances relevance and accessibility for diverse student populations. However, students with significantly lower proficiency levels may still face challenges in comprehension, underscoring the need for additional assessment-driven personalisation mechanisms. The performance-scoring system embedded within the chatbot provides useful motivational incentives, although its long-term effectiveness remains uncertain. Authentic motivation in STEM often arises from inquiry, discovery, and experiential learning, dimensions that cannot yet be fully replicated by autonomous systems. A potential drawback of AI-driven interaction is the tendency for students to seek immediate answers without pursuing deeper inquiry. This behaviour may limit their ability to examine multi-causal phenomena or develop holistic problem-solving skills. Encouraging critical evaluation and exploration from multiple angles is therefore vital.

In terms of strengths, the chatbot aligns well with contemporary educational goals. It offers personalised learning paths (Chan & Hu, 2023), delivers rapid responses (Limna et al., 2023), supports creative idea generation (Akiba & Fraboni, 2023; Liang et al., 2023), and enhances learning outcomes (Wandelt et al., 2023).

Future research opportunities include expanding the chatbot's feature set to support engagement and academic achievement further. Studies could evaluate whether AI-generated visuals enhance user experience, or whether performance-linked assessment contributes to improved learning outcomes, problem-solving capabilities, and knowledge retention. Integrating chatbot programming into IT and STEM curricula could also reinforce 21st-century skills. From a teacher's perspective, examining attitudes toward chatbot development and usage is equally valuable. Embedding pedagogical models such as Bloom's taxonomy (Ravichandran & Virgin B, 2024) may offer an effective framework for developing chatbot-based assessments.

To date, the system has not been introduced to educational stakeholders. Further review is necessary to evaluate its practical application and classroom readiness. Based on deployment outcomes, future iterations may require updates informed by feedback from students, teachers, and parents. Resource limitations, including free-tier access, operating-system compatibility, and emoji rendering, also restricted broader testing.

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Qualitative Metrics

Next, the results were compared to those of the original BUS-15 questionnaire (Table 5).

Table 5
Comparison of Average Scores for Each Factor Between the Current Study and the Original Questionnaire

Factor	This study	Borsci et al. (2022)	Difference
Accessibility	3.34	3.62	-0.28
Function quality	2.99	3.78	-0.79
Conversation quality	2.72	3.6	-0.88
Privacy and security	3.31	3.52	-0.21
Time response	2.78	3.3	-0.52

Compared to the original findings of Borsci et al. (2022), I found lower average scores across all five BUS-15 factors, with differences ranging from −0.21 to −0.88. Several contextual variables may account for this disparity. First, participants interacted with the chatbot in English, which was not their native language. Their age and limited proficiency may have adversely affected the perceived conversation quality. Second, cultural response patterns likely played a role: respondents from Southeast Asia are generally inclined to avoid extreme Likert-scale ratings (Harzing, 2006). Third, the study was conducted in a live classroom setting, which may have elicited more critical feedback compared to evaluations in more controlled environments. Finally, variability in prior exposure to AI tools, along with the relative developmental maturity of the chatbot, could have influenced participants' usability assessments.

General Discussion

This pilot study provides valuable information on the usability of the proposed AI system and its initial phase of development. However, future research should repeat the analysis with a larger and more diverse participant base to enhance generalisability. A key operational metric is the number of interactions between students and the system: although classroom planning anticipated 1,200 to 1,500 chatbot queries, usage logs showed approximately 3,500 question–answer pairs, reflecting unexpectedly high engagement. Future studies should incorporate a dedicated interaction counter linked to individual users, rather than relying solely on session time, which is prone to inaccuracy when users neglect to log out.

This research had several limitations. As a pilot with a modest sample size, it may not have captured the full scope of usability challenges or design opportunities, reinforcing the need for larger-scale replication. The BUS-15 questionnaire was administered within a single 90-minute session, and the scope was limited to student-facing content. Although the chatbot also includes roles for parents and teachers, such as academic monitoring, calendar management, and parent–teacher interaction, these functions were not examined. Language barriers further complicated interaction quality. Operating solely in English, the chatbot presented comprehension challenges for students unfamiliar with the language, resulting in misinterpretations and repeated queries. Enhancing conversation quality requires systematic validation of translations and revision of instructional phrasing. In addition, the user guide should be updated to provide clearer, step-by-step instructions and contextual examples of system functionality.

Conclusions and Implications

This study underscores the potential of generative AI, particularly customised chatbots, as a key component in enhancing student–computer interaction within STEM education. The increasing demand for personalised and interactive learning experiences highlights the importance of developing accessible, student-friendly applications. The chatbot, developed using the Botpress platform, benefited from a flexible and robust framework suitable for educational deployment. Such tools can effectively support student engagement and complement existing teaching practices.

However, the analysis revealed that chatbot development is not universally accessible to educators. A lack of programming expertise and technical background may limit participation. Therefore, collaboration between

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educators and IT specialists is essential during development, as is continued training and support to build technological confidence.

The study highlights new curricular opportunities in programming education. First, further empirical research is needed to explore the use of AI-powered chatbots in teaching programming languages. While current tools can generate syntactically accurate code across most languages, they fall short in fostering computational thinking and debugging skills. A well-designed, customised chatbot could help identify student knowledge gaps and cultivate deeper analytical reasoning. Second, the integration of chatbot development into IT curricula represents a valuable addition to traditional programming instruction. Although foundational languages such as Python, C++, and JavaScript remain critical, competency in chatbot design offers a unique and increasingly relevant skillset for the workforce.

AI-based applications also show promise for boosting student interest in STEM subjects. This small-scale pilot serves as an initial step toward embedding AI tools within pedagogical frameworks. The goal is not to deliver cutting-edge systems for their own sake but to support learner growth, motivation, and achievement. Realising this goal requires expanded research, functional enhancements, and sustained pedagogical integration to prepare students adequately for the digital future of education.

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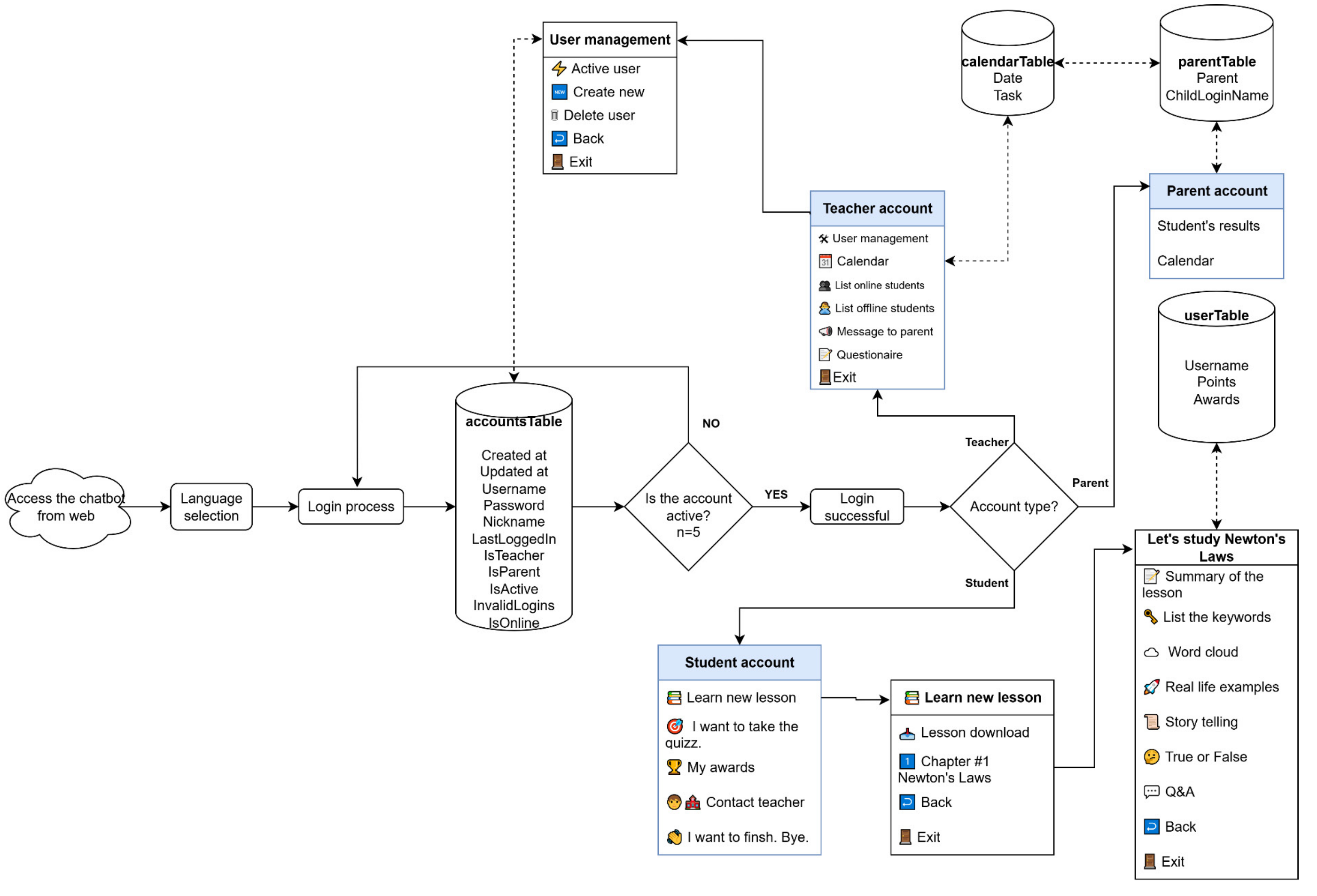
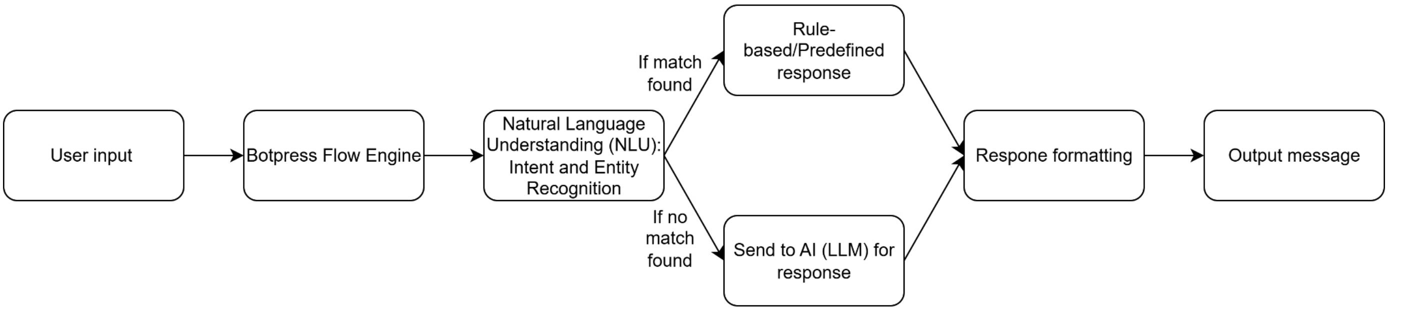
Appendix

The Developed Chatbot's Functions and Services



The Botpress GUI and the AI Model Integration



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JUDGING INVASIVENESS UNDER SCIENTIFIC UNCERTAINTY: VALUE ORIENTATIONS AND REASONING PATTERNS OF PRE-SERVICE BIOLOGY TEACHERS ON THE GOLDEN APPLE SNAIL

Hyojeong Hwang,
Jun-Ki Lee

Abstract. *In the Anthropocene era, science educators must equip students to reason through uncertainty and navigate value-laden environmental dilemmas. This study aimed to examine how pre-service biology teachers make value-based decisions when facing scientific uncertainty, using the case of the golden apple snail (Pomacea canaliculata) and its designation as an invasive species. Drawing on the framework of post-normal science and environmental ethics, a scenario-based mixed-methods survey was conducted with 191 participants across five universities in South Korea. Quantitative results showed that 69.1% of respondents supported the designation, typically adopting ecocentric and precautionary perspectives, while 30.9% opposed it, citing anthropocentric pragmatism and techno-optimism. Qualitative analysis revealed confirmation bias and temporal framing patterns, with participants selectively interpreting evidence in ways consistent with their prior value orientations. These findings highlighted the importance of fostering uncertainty literacy, critical thinking, and ethical reasoning in science teacher education. The study offers international relevance by addressing how future educators construct environmental judgments under uncertainty, with implications for curriculum design across diverse socio-ecological contexts.*

Keywords: *invasive species, decision making, pre-service teachers, scientific uncertainty, value orientation*

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Introduction

In the Anthropocene era, the interlinked crises of climate change, biodiversity loss, and invasive species have become defining challenges for ecosystems and human societies. These unprecedented conditions demand new ways of thinking about science education and environmental decision-making, as emphasized by previous research (Crutzen & Stoermer, 2000; Lee & Park, 2024; Steffen et al., 2015). These challenges are further complicated by the volatility, uncertainty, complexity, and ambiguity (VUCA) of the conditions that define our era, where scientific knowledge is often incomplete, evidence is contested, and the consequences of decisions are far-reaching and unpredictable (Funtowicz & Ravetz, 1993; Wals & Jickling, 2002). In this context, the role of science education, and the preparation of future science teachers in particular, has become increasingly significant, as teachers are called upon to foster not only scientific literacy but also the ability to reason through uncertainty and navigate value-laden dilemmas (Jeong et al., 2021; Sadler, 2004; Yavuzkaya et al., 2024; Zeidler et al., 2005).

The golden apple snail (*Pomacea canaliculata*) provides a compelling case study examining how pre-service biology teachers approach scientific uncertainty and value conflict. Introduced in South Korea in 1983 as a biocontrol agent for eco-friendly rice farming, this snail species initially contributed to reducing herbicide use and has been widely adopted in sustainable agriculture. However, their rapid reproduction and adaptability have led to their designation by the International Union for Conservation of Nature as one of the 100 most invasive species worldwide, causing significant ecological and agricultural concerns in several countries (Bang & Cho, 2008; Lowe et al., 2000). Climate change further complicates this situation because rising

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winter temperatures may enable snails to survive and proliferate in new regions, increasing the risk of ecological disruption (IPCC, 2021; Steffen et al., 2015).

Despite the global relevance of invasive species management and the growing importance of uncertainty reasoning in science education, few studies have explored how future educators make value-laden decisions in contexts characterized by ambiguous or conflicting evidence. Empirical research on pre-service biology teachers' reasoning patterns and value orientations under scientific uncertainty remains limited, particularly in the East Asian context.

This gap is significant, given that their personal frameworks of reasoning and ethics may influence how they teach complex environmental issues.

Socioscientific issues such as the designation of invasive species are inherently complex and controversial, requiring decision makers to weigh scientific evidence, ethical considerations, and the interests of diverse stakeholders (Sadler, 2004; Zeidler et al., 2005). In such contexts, scientific knowledge alone is often insufficient for decision-making; individuals must integrate empirical data with value judgments, risk perceptions, and societal priorities (Funtowicz & Ravetz, 1993; Kortenkamp & Moore, 2001). Studies have shown that the reasoning of pre-service teachers regarding socioscientific issues is influenced by their understanding of science and ethical orientations, worldviews, and experiences (Jickling & Wals, 2008; Sadler & Zeidler, 2005). For example, some may adopt an ecocentric perspective, emphasizing the intrinsic value of nature and the precautionary principle, whereas others may prioritize human utility, technological optimism, or pragmatic solutions to environmental problems (Dryzek, 2013; Naess, 1973).

Furthermore, the lack of explicit instruction in uncertainty reasoning, critical thinking, and ethical deliberation in many teacher education programs highlights the urgent need for curriculum reforms. By examining how pre-service biology teachers interpret evidence and negotiate value-laden decisions under real-world ecological uncertainty, this study provides insight into how teacher education can evolve to better prepare future educators.

Despite the recognized importance of uncertain reasoning and value negotiations in science education, many teacher preparation programmes continue to focus on transmitting established knowledge and scientific consensus, neglecting the skills needed to address ambiguities, controversies, and ethical complexities (Halpern, 2014; Lotz-Sisitka et al., 2015). This gap is particularly problematic in the Anthropocene, where environmental issues are rarely clear-cut and often require balancing competing values and uncertain outcomes (Crutzen & Stoermer, 2000; Steffen et al., 2015). As future educators, pre-service biology teachers must be equipped to teach scientific facts and guide students through critical reflection, ethical deliberation, and informed decision-making in the face of uncertainties (Wals & Jickling, 2002; Zeidler et al., 2005).

This need was addressed by examining how Korean pre-service biology teachers evaluate ambiguous ecological and agricultural information concerning the golden apple snail, and how distinct ethical and cognitive orientations influence their decisions. By foregrounding both the international relevance of invasive species issues and the under-examined dimension of uncertainty reasoning in teacher education, this study contributes to global discussions on science pedagogy in complex socio-ecological contexts. Unlike previous studies focusing primarily on content knowledge or socioscientific argumentation, this study uniquely integrated ecological uncertainty, ethical reasoning, and cognitive framing into teacher education research.

Theoretical Framework

Socioscientific Issues and Post-Normal Science

Socioscientific issues are complex, real-world problems that require individuals to integrate scientific evidence with ethical reasoning and social values, often under conditions of uncertainty and controversy (Sadler, 2004; Zeidler et al., 2005). Post-normal science involves situations in which facts are uncertain, values are disputed, and decisions are urgent—characteristics common to contemporary environmental challenges, such as invasive species management and climate change adaptation (Funtowicz & Ravetz, 1993). In this context, science education must move beyond the transmission of settled knowledge to foster skills for navigating ambiguity, deliberating values, and making informed decisions in the face of incomplete evidence (Jickling & Wals, 2008; Wals & Jickling, 2002).

This framework has been increasingly applied in science education to examine how learners and teachers respond to ill-structured problems lacking clear solutions (Lotz-Sisitka et al., 2015; Zeidler et al., 2005). Sadler and Zeidler (2005) demonstrated that post-normal conditions elicit diverse informal reasoning strategies among students. However, relatively few studies have investigated how pre-service teachers, as future decision facilitators, engage in post-normal dilemmas in environmental decision-making. This study is built on post-normal science

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by focusing on how candidate teachers interpret and respond to value-laden ecological uncertainty in the case of the golden apple snail.

Environmental Ethics and Value Orientations

Ethical frameworks deeply influence environmental decision-making, particularly the tension between ecocentrism and anthropocentrism (Kortenkamp & Moore, 2001; Naess, 1973). Ecocentric perspectives emphasize the intrinsic value of nature and the integrity of ecosystems, advocating the precautionary principle when faced with ecological uncertainty (O'Riordan & Cameron, 1994). In contrast, anthropocentric or pragmatic approaches prioritize human utility, technological solutions, and adaptive management, often favoring innovation and risk-taking over precautions (Dryzek, 2013). These value orientations influence how teachers and students perceive scientific uncertainty and make decisions concerning environmental management, as evident in debates over the invasive status of species such as the golden apple snail (Sadler & Zeidler, 2005).

This duality in value orientation has been observed in environmental philosophy and science education research. Zeidler et al. (2005) emphasized that value-based reasoning is central to socioscientific decision making, particularly when learners are confronted with ethically ambiguous information. Recent studies have investigated how students and teachers adopt different ethical stances depending on contextual framing (Sadler, 2004; Yavuzkaya et al., 2024). However, few studies have examined how these orientations manifest in the reasoning of pre-service biology teachers under ecological uncertainty.

Patterns in Information Processing and Uncertainty Reasoning

When individuals encounter ambiguous or controversial information, their prior beliefs and values often influence how they interpret and recall the evidence (Klayman & Ha, 1987; Mercier & Sperber, 2011). In environmental issues, people may focus on data supporting their initial stance while downplaying or reinterpreting contrary evidence, leading to persistent differences in judgment even when presented with the same facts (Sadler, 2004; Halpern, 2014). This tendency can reinforce polarization and hinder balanced deliberation in environmental controversies. Addressing these information processing patterns is a key challenge in science education and requires explicit instruction in critical thinking, argumentation, and metacognitive reflection (Halpern, 2014; Lotz-Sisitka et al., 2015). These skills need to be integrated into teacher education so that educators are equipped and prepared to help students adopt nuanced, reflective, and participatory approaches to science learning in the Anthropocene era (Wals & Jickling, 2002).

Confirmation bias has been identified as a key barrier in fostering critical engagement on controversial issues in science education. For instance, Halpern (2014) argued that without explicit metacognitive training, learners process socioscientific information in ways that reaffirm their preexisting positions. This study built on such insights by analyzing how pre-service teachers interpret the same ecological and agricultural claims differently depending on their value orientations. It revealed patterns of selective attention, reinterpretation, and temporal framing.

Research Aim and Research Questions

This study examined how pre-service biology teachers make value-based decisions under scientific uncertainty in the context of environmental controversy. Specifically, it examined how they justify their support for or opposition to designating the golden apple snail (*P. canaliculata*) as an invasive species and how ethical orientations and information processing patterns influence their reasoning. Grounded in the framework of post-normal science and socioscientific issues, this study sought to reveal the interplay between scientific evidence, personal values, and cognitive strategies that influence environmental decisions among future science educators.

The following research questions were formulated to address this aim:

RQ1. How do pre-service biology teachers justify their support for or opposition to designating the golden apple snail as an invasive species under scientific uncertainty, and what value orientations characterize these decisions?

RQ2. What reasoning and evidence interpretation patterns emerge when pre-service biology teachers encounter conflicting ecological and agricultural information on golden apple snails?

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Research Methodology

Design and Context

This study used an exploratory sequential mixed-methods design (Creswell & Clark, 2017), combining quantitative and qualitative approaches, to examine how pre-service biology teachers reason through scientific uncertainty. It was conducted during the spring semester of 2023 at five universities in South Korea.

Grounded in the frameworks of socioscientific issues (Zeidler et al., 2005) and post-normal science (Funtowicz & Ravetz, 1993), the study focused on teachers' decision-making processes in the face of ambiguous ecological and agricultural information.

Participants

One hundred ninety-one pre-service biology teachers from five universities in South Korea were enrolled in the study. The sample size was not predetermined by statistical calculation; instead, it reflected the full number of students who were available and consented to participate across the five universities at the time of data collection. The participants ranged from first- to fourth-year undergraduate students majoring in biology education, comprising 67 males (35.1%), 123 females (64.4%), and one participant who did not disclose gender. This individual was excluded from gender-based statistical analyses. Because the study included students from multiple regions and all academic levels, the sample ensured contextual diversity and representativeness within the scope of Korean biology teacher education programs. Participants were informed of the study's aims, ethical considerations, and data confidentiality and voluntarily provided informed consent. This study was conducted in accordance with the institutional ethical guidelines.

Instruments

The participants were presented with a scenario[Appendix 1] describing golden apple snails' ecological and agricultural impacts, including conflicting expert opinions and climate change projections. The researcher carefully constructed a scenario based on diverse online news articles, expert commentaries, and public reports on using golden apple snails in Korean agriculture. These sources were selected to reflect the socio-political and environmental contexts of *P. canaliculata* management in South Korea. Foundational insights from prior research on this species' ecological risks and global invasive status were also incorporated (Bang & Cho, 2008; Lowe et al., 2000). The scenario, a fictionalized yet realistic dialogue between two ecologists with opposing views, was designed to simulate the value-laden and scientifically uncertain debates that characterize real-world socioscientific issues.

The content was based on controversies observed in South Korea regarding the ecological risks and agricultural benefits of introducing the golden apple snail, enhancing the instrument's contextual and ecological validity. The structured questionnaire consisted of the following questions.

- A binary choice on whether to designate the snail as an invasive species.
- Open-ended questions probing the rationale for their decision.
- Items asking which information most influenced their judgment.
- Requests for detailed justification of their stance.

Two science education experts and an environmental scientist reviewed the scenario and questionnaire to ensure content validity. Their feedback was used to revise potentially ambiguous statements and ensure alignment with the theoretical constructs addressed in this study.

Data Collection and Analysis

Data were collected during scheduled class sessions in the spring of 2023. Following this, 191 pre-service biology teachers read a detailed explanation of the purpose of the study and provided voluntary, informed consent for participation. The average response time was 25–30 minutes, allowing participants to reflect deeply on the invasive species scenario (Creswell & Clark, 2017). Quantitative responses were analyzed using descriptive statistics and cross-tabulations to identify overall decision trends and demographic patterns according to sex and academic year (Field, 2013). Chi-square tests were conducted to determine whether statistically significant differences existed between the decision outcomes and participant characteristics.

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Qualitative data were analyzed using thematic analysis based on a constant comparative method (Braun & Clarke, 2006). Two researchers independently read all open-ended responses and extracted discrete meaning units based on recurring patterns in language and reasoning. Through iterative comparisons and discussions, emergent codes were developed and refined until a consensus was reached.

These codes were then grouped into broader themes, including ecosystem guardianship, future risk prevention, eco-pragmatism, and techno-optimism, which were mapped onto theoretical constructs such as the precautionary principle and the ecocentrism–anthropocentrism spectrum (Kortenkamp & Moore, 2001). This analytical process aimed to preserve the integrity of the participants' voices while enhancing the credibility and trustworthiness of the findings.

Research Results

Quantitative Results

Of the 191 pre-service biology teachers, 132 (69.1%) supported the designation of the golden apple snail as an invasive species, and 59 (30.9%) opposed it. Chi-square tests revealed no statistically significant associations between designation decisions and gender ($\chi^2(1) = .31$, $p = .58$) or academic year ($\chi^2(3) = 1.95$, $p = .58$). This suggested that demographic variables such as gender and academic level were not significantly associated with participants' decisions.

Among the 132 participants, 86 (65.2%) expressed ecosystem guardianship, 23 (17.4%) expressed agricultural realism, 15 (11.4%) expressed future risk prevention, 5 (3.8%) expressed integrated concerns, and 3 (2.3%) expressed scientific principles. Among the 59 anti-designation participants, 32 (54.2%) expressed eco-pragmatism, 13 (22.0%) expressed techno-optimism, 9 (15.3%) expressed cautious synthesis, 3 (5.1%) expressed biodiversity enhancement, and 2 (3.4%) expressed status-quo advocacy.

Qualitative Results

Value Orientations in Reasoning

Qualitative analysis identified distinct reasoning patterns associated with the participants' value orientations. The pro-designation group predominantly invoked ecocentric and precautionary rationales. Participants emphasized the value of native species, the unpredictability of ecological impacts, and the need to prevent irreversible harm. They also cited the potential risks of ecosystem disruption and long-term invasiveness.

Within the pro-designation group, value orientations included ecosystem guardianship, future risk prevention, scientific principles, agricultural realism, and integrated concerns. For instance, one participant noted, "If winters get warmer, snail populations will explode, threatening native ecosystems," which reflects a long-term ecological concern.

In contrast, the anti-designation group emphasized the benefits of using snails in agriculture and the manageability of potential risks. Their value orientations include eco-pragmatism, techno-optimism, biodiversity enhancement, status quo advocacy, and cautious synthesis. A representative response reflecting eco-pragmatism was, "Using snails reduces pollution and boosts biodiversity." Table 1 presents the value orientations and representative responses related to participants' decisions regarding the invasive status of golden apple snails.

Table 1
Distribution of Value Orientations Among Pre-Service Biology Teachers Regarding the Invasive Species Designation

Value orientation	Pro-designation	Anti-designation	Representative response
Ecosystem guardianship	86 (65.2)	N/A	"If winters get warmer, snail populations will explode, threatening native ecosystems."
Future risk prevention	15 (11.4)	N/A	"Climate change may enable snail proliferation, so early action is essential."

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Value orientation	Pro-designation	Anti-designation	Representative response
Scientific principlism	3 (2.3)	N/A	"Global IUCN guidelines list this species as invasive, so precaution is warranted."
Agricultural realism	23 (17.4)	N/A	"They devour rice seedlings faster than we can remove them."
Integrated concerns	5 (3.8)	N/A	"Weighing ecosystem integrity and farm productivity led me to support the designation."
Eco-pragmatism	N/A	32 (54.2)	"Using snails reduces pollution and boosts biodiversity."
Techno-optimism	N/A	13 (22.0)	"With proper management, harm is minimal."
Biodiversity enhancement	N/A	3 (5.1)	"New species appeared in snail-infested fields, increasing diversity."
Status quo advocacy	N/A	2 (3.4)	"No major harm has been documented, so current practices should continue."
Cautious synthesis	N/A	9 (15.3)	"Adaptive management with ongoing research offers a middle path."
Total	132 (100%)	59 (100%)	

Notes: Percentages reflect orientation-specific counts among proponents (first five) or opponents (last five) of the invasive species designation. Representative responses were drawn from survey data. IUCN: International Union for the Conservation of Nature. n = 191, values reflect frequency and percentage.

Cognitive Reasoning Patterns

Confirmation bias was commonly observed; participants often interpreted the same information (e.g., increased biodiversity) in ways that supported their stance. For instance, pro-designation participants viewed short-term biodiversity gains as temporary and outweighed long-term risks, whereas anti-designation participants viewed the same data as evidence of compatibility.

These interpretations aligned with the participants' value orientations. Eco-pragmatic or techno-optimistic participants focused on short-term benefits, whereas those aligned with ecosystem guardianship or future risk prevention emphasized the importance of precaution.

Temporal framing also played a significant role. Pro-designation participants emphasized long-term ecological risks and responsibilities, whereas anti-designation participants highlighted immediate benefits and feasibility. These reasoning patterns were classified based on the participants' references to timing and interpretation.

Table 2 summarizes the cognitive reasoning patterns identified in the participants' responses, categorized by confirmation bias and temporal framing subtypes.

Table 2
Cognitive Reasoning Patterns Used by Participants in Interpreting Scientific Uncertainty

Cognitive pattern	Subtype	Description	Example response
Confirmation bias	Selective attention	Focusing only on evidence that supports one's prior belief while downplaying or ignoring contradictory information	"Short-term diversity gains are misleading anomalies overshadowed by long-term species loss."
	Counterevidence discount	Minimizing or reframing disconfirmation data to align with one's existing viewpoint	"Managed snail populations offer agricultural benefits without causing lasting ecological harm."
	Reinterpretation	Recasting identical information to fit one's original position, despite neutral or opposing contexts	"Increased biodiversity proves ecological compatibility, not invasion."

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Temporal framing	Future-risk emphasis	Emphasizing long-term, intergenerational risks to justify precautionary or protective measures	"If warming continues, uncontrolled snail proliferation will irreversibly alter habitats for future generations."
	Present-benefit emphasis	Highlighting immediate advantages and feasibility to support continuation of current practices	"Today's gains in crop productivity and reduced herbicide use justify ongoing snail management rather than premature restriction."
	Balanced-time framing	Integrating both near-term benefits and long-term risks to propose moderated, adaptive solutions	"Adaptive management now and further studies later offer a balanced approach to address both immediate needs and future uncertainties."

Discussion

Pre-service biology teachers who supported the invasive species designation of the golden apple snail often prioritized ecological integrity and the intrinsic value of native species, reflecting an ecocentric worldview (Funtowicz & Ravetz, 1993). They argued that uncertain long-term ecological impacts such as disrupted food webs and declining biodiversity warrant precautionary measures to prevent irreversible harm (O'Riordan & Cameron, 1994). This group tended to perceive ecological risk through a future-oriented lens, aligning with the precautionary principle, particularly relevant in post-normal science contexts characterized by complexity, uncertainty, and value-laden decisions (Funtowicz & Ravetz, 1993). In contrast, those opposing the designation have frequently adopted anthropocentric and pragmatic rationales, emphasizing the role of snails in reducing herbicide use and bolstering short-term agricultural productivity (Kortenkamp & Moore, 2001). This reflects a present-focused, utility-based assessment of ecological intervention and illustrates a techno-optimistic perspective, in line with Dryzek's (2013) characterization of pragmatic environmentalism. This dichotomy mirrors broader environmental ethics debates in which ecocentric and anthropocentric frameworks offer competing prescriptions for managing ecological uncertainty (Naess, 1973).

The precautionary principle advocates for preventive action when scientific uncertainty surrounds potentially serious environmental harm (O'Riordan & Cameron, 1994). Pro-designation teachers invoked this principle to justify early intervention, citing climate change projections that could enable snails to invade new regions (IPCC, 2021). They argue that delaying action until conclusive evidence emerges risks irreversible ecological damage, which is consistent with post-normal scientific thinking in the context of high uncertainty and contested value (Funtowicz & Ravetz, 1993). However, opponents have questioned the adequacy of the precaution-based approach, expressing confidence in adaptive management tactics to control snail populations without resorting to invasive species designations (Dryzek, 2013). This contrast demonstrated how differing environmental ethics and attitudes toward uncertainty can lead to divergent policy preferences, underscoring the importance of incorporating precautionary and adaptive frameworks in science education (Zeidler et al., 2005). This discussion further reinforces the answer to RQ1 by illustrating how contrasting ethical perspectives (precautionary vs. adaptive) shaped participants' judgments.

Teachers' interpretations of ambiguous biodiversity data revealed a tendency toward confirmation bias, in that individuals tended to favor evidence that supported their existing viewpoints (Klayman & Ha, 1987). The pro-designation respondents viewed short-term increases in biodiversity as transient anomalies that long-term declines in native species would overshadow. In contrast, the anti-designation proponents considered the same data proof of ecological compatibility (Sadler & Zeidler, 2005). These contrasting interpretations of identical data underscore how deeply values influence cognitive evaluations of evidence, a pattern consistent with prior research emphasizing the value-ladenness of socioscientific reasoning (Sadler & Zeidler, 2005). This selective interpretation underscores the challenge of fostering balanced deliberation in environmental controversies and highlights the need for metacognitive strategies to help teachers and students recognize and mitigate bias (Halpern, 2014). These findings respond to RQ2, which examined what reasoning patterns emerge when pre-service teachers interpret conflicting information on golden apple snails.

Temporal framing also played a significant role, with supporters of the invasive species designation emphasizing long-term risks and intergenerational responsibility, while opponents prioritized immediate agricultural benefits and feasibility (Ojala, 2012; Slovic, 1987). Such temporal framing suggested that the time horizon is a critical lens through which ecological risk is perceived and acted upon and underscores the pedagogical value of explicitly

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addressing how different timeframes influence environmental decision-making (Ojala, 2012). This emphasis on confirmation bias and temporal framing directly addresses RQ2, highlighting the cognitive processes underlying participants' reasoning under uncertainty.

The observed diversity of value orientations and reasoning patterns highlighted the importance of integrating uncertainty literacy, ethical reasoning, and critical thinking into science teacher education programmes (Jickling & Wals, 2008). Teacher preparation should include case-based learning concerning socioscientific issues, emphasizing the nature of scientific uncertainty and the precautionary principle, and teaching adaptive management frameworks to address techno-optimistic perspectives (Zeidler et al., 2005). Structured argumentation exercises can help pre-service teachers recognize and counter confirmation bias, fostering metacognitive reflection and balanced deliberation (Mercier & Sperber, 2011). Furthermore, role-play simulations of stakeholder debates can cultivate empathy and broaden ethical horizons, preparing educators to guide students through complex environmental decisions (Lotz-Sisitka et al., 2015).

Teacher education curricula should integrate explicit training modules on value negotiation, evidence appraisal, and uncertainty framing to translate these insights into practice. Incorporating Toulmin-based argument mapping, reflective journaling, and simulation-based decision-making tasks can support the development of adaptive reasoning under ambiguous conditions. By equipping future educators with such tools and habits, science education can move beyond content delivery to cultivate reflective, ethically grounded professionals capable of engaging with the socio-ecological challenges of the Anthropocene.

Conclusions and Implications

This study demonstrated that, as future science educators, pre-service biology teachers brought diverse value orientations and reasoning strategies to their judgments when confronted with scientific uncertainty regarding the designation of the golden apple snail as an invasive species. Their decisions reflected multiple perspectives, including ecocentric and anthropocentric orientations, precautionary thinking and techno-optimism, and temporal considerations prioritizing long-term ecological risks or immediate agricultural benefits. Selective information processing and confirmation bias were prevalent, with participants often interpreting ambiguous or conflicting evidence to reinforce their initial value positions, reflecting broader patterns of value-laden reasoning commonly observed in socioscientific decision-making.

These findings highlight the need for science teachers to move beyond knowledge transmission and explicitly foster uncertainty literacy, critical thinking, and ethical deliberation.

Although this study was conducted in South Korea, its implications resonate with the global debates on invasive species management under scientific uncertainty. It offers valuable insights into how future science teachers construct meaning and make decisions in ethically and ecologically complex contexts. The study also contributes to broader discussions in science education regarding socioscientific reasoning, teacher beliefs, and sustainability-oriented pedagogy, which are increasingly emphasized in recent scholarship and educational reform agendas.

Teacher preparation should incorporate practical tools such as scenario-based simulations, argument mapping, and structured ethical debates to help pre-service teachers engage with real-world dilemmas and practice value negotiations. Reflective journaling and role-playing can strengthen metacognitive awareness, enabling teachers to guide students through ethically complex classroom decisions. By integrating such approaches, science education can cultivate reflective and ethically responsible professionals prepared to navigate the socio-ecological challenges of the Anthropocene.

This study has several limitations. First, a scenario-based survey, useful for eliciting structured reasoning, may not fully capture how pre-service teachers would make decisions in real-world contexts, such as classrooms, curricula, or public policy discussions. A social desirability bias may have influenced participants, potentially framing their justifications in ways they believed were ethically or environmentally acceptable.

Second, although qualitative coding was rigorously performed with the researchers reaching a consensus, the thematic mapping process inherently involved interpretive judgments that may have influenced how certain responses were classified under specific value orientations. While methodologically valid, this interpretive nature calls for caution when generalizing typologies beyond this study.

Third, the participant sample consisted solely of biology students from South Korea. The study's findings may not directly apply to different national or disciplinary contexts despite offering insights into culturally relevant environmental issues.

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Future research should explore how sustained engagement with socioscientific controversies influences the development of ethical reasoning and tolerance for uncertainty among pre-service teachers. Longitudinal studies could examine how targeted instructional interventions, such as ethics modules or adaptive management tasks, shape value orientations and decision-making strategies. In addition, cross-cultural comparisons would be valuable for understanding how educators in different educational systems draw on distinct ethical or epistemic frameworks when addressing environmental uncertainty.

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Declaration of Interest

The authors declare no competing interest.

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Appendix 1.

Dialogue Used in the Survey: Debate between Ecologists on the Golden Apple Snail

The following is a fictional dialogue between ecologists Dr. Kim and Dr. Lee regarding the designation of the golden apple snail (currently listed as an "ecological risk species" in Korea) as an invasive alien species. Please read it carefully and respond to the questions below.

Dr. Kim: One of our country's most significant challenges in rice farming is weeds. They grow endlessly everywhere and reduce the rice yield. However, using herbicides to remove weeds can cause environmental pollution, so we need to be cautious. That is why, since the 1990s, we have been using golden apple snails to eliminate weeds. They are very efficient—capable of removing up to 98% of all weeds. Golden apple snails make eco-friendly farming possible by increasing rice yield without causing environmental damage.

Dr. Lee: But golden apple snails are a species introduced from tropical regions. They reproduce rapidly and have a broad appetite, eating weeds, water parsley, and even native snails. They have been designated as an "ecological risk species" in Korea. The International Union for Conservation of Nature even listed them among the world's 100 most invasive alien species.

Dr. Kim: However, golden apple snails cannot survive winter in Korea. If temperatures drop below –3 °C for just three days, they die. According to a local government report, the golden apple snails' population decreased significantly because they could not endure winter, and no single case of damage caused by them was reported. Because Korea has cold winters, it is not as suitable for golden apple snails as other countries.

Dr. Lee: Due to climate change, winter temperatures in southern Korea have become warmer than average. There have been cases in the south where golden apple snails survive winter. This phenomenon gradually spread northward. As a result, some local governments have set up dedicated periods after the rice harvest to collect snails. If they survive winter, they can harm young rice plants by nibbling during the spring planting season.

Dr. Kim, an expert in eco-friendly agriculture, has stated that if appropriately managed, golden apple snails will not pose a significant threat to the ecosystem. Farmer Kim ○○, who has been using golden apple snails for over 10 years, also mentioned that he has experienced almost no problems. In contrast, since herbicides are not used, organisms such as tadpole shrimp have reappeared, and biodiversity has increased. Golden apple snails are inexpensive and enable environmentally friendly rice farming. As of 2018, 88.9% of the eco-friendly rice farms in Korea have been using golden apple snails. Therefore, their designation as invasive species would significantly harm eco-friendly farming practices.

Dr. Lee: Golden apple snails damage other crops and ecosystems and harm rice farming by feeding on young rice shoots. Mr. Park, a village head in △△ the Village, lamented that just two snails ate an entire rice plant within an hour. In 2020, approximately 17% of the area's total farmland (approximately 600 soccer fields) was damaged by golden apple snails. Countries such as Taiwan, Japan, and Vietnam have banned snail farming. We cannot predict the type of damage that this species might cause to Korean ecosystems in the future. Therefore, golden apple snails must be considered invasive to prevent future large-scale damage.

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COMPARISON OF TEACHING AND LEARNING CONCEPT NETWORKS RELATED TO ECOSYSTEM COMPOSITION IN UPPER SECONDARY SCHOOLS IN REPUBLIC OF KOREA

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Abstract. *Learning in the classroom is mainly done through verbal interaction. Since science learning is a subject in which it is difficult for students to acquire knowledge on their own, teacher guidance in class is more important. This study aimed to compare teaching and learning concept networks for the ecosystem-related content taught in upper secondary schools in the Republic of Korea. This content is divided into two classes—namely, 'Ecosystem Components' and 'Interactions between Ecosystem Components'. The key concept and connection networks for teaching and learning concepts were analysed. The study participants were 10th-grade students and three teachers who taught them. The teacher's class content was recorded, while the students' learning concepts were examined using a questionnaire. The collected data were analysed using NetMiner 4.0. The results of this study are as follows: First, the teachers and students predominantly shared the concept of the entire ecosystem; however, the detailed structures of the concept networks differed. Second, the teacher did not clearly teach the concepts of the 'Ecosystem Components' and 'Interactions between Ecosystem Components' classes and utilised the concepts repeatedly. Third, the follow-up learning content impacted the pre-learning. These findings suggest that teachers need to clearly divide concepts into each topic when teaching.*

Keywords: *ecosystem composition, upper secondary school, teaching concept network, learning concept network, connection network*

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Introduction

Learning in the classroom is accomplished through interaction between teachers and students. Most of this interaction is done through language. Learning in the classrooms is accomplished through teachers conveying knowledge, or concepts to students through verbal interaction. An important goal of education is helping students understand scientific concepts (Gauld, 2001; MOE, 2015; Smith & Siegel, 2004). Specifically, as independently acquiring knowledge in science is challenging for students, they learn most scientific concepts through teacher guidance in class (Mallow, 1986).

Learning outcomes differ significantly depending on how teachers plan and implement classes in schools (Pianta & Hamre, 2009; Powell & Anderson, 2002; Schenke et al., 2017; Waller, 2006). However, teachers—despite aiming to facilitate students' concept formation through explanation—generally do not consider how students understand and construct cognitive structures for these concepts (Widodo & Duit, 2002; Widodo et al., 2002). Therefore, teachers should understand the conceptual structure that they use to explain concepts and the one that students employ to acquire concepts in class (Chun et al., 2024; Lim et al., 2024).

Semantic network analysis (SNA) is primarily utilised to determine the structure of concepts in students' cognitive structures (Choi et al., 2017). It has the advantage of concretising abstract semantic structures by analysing the connection patterns between concepts and visualising hidden structures (Doerfel & Barnett, 1999).

Previous studies employing SNA methods have analysed connections between concepts (Chung et al., 2018; Kim & Kwon, 2016; Kim et al., 2019) and students' concept networks (Lim et al., 2020). Additionally, studies have analysed teachers' teaching concepts and students' learning concepts. For

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example, studies have investigated these concepts vis-à-vis Mendelian principles of inheritance (Kim et al, 2023; Lim et al., 2024) and photosynthesis (Chun et al., 2024; Yoo et al., 2024) units in lower secondary school; these studies must be expanded by targeting upper secondary school students.

In the Republic of Korea's curriculum, ecosystem-related content is taught in elementary and upper secondary schools. In upper secondary schools, students are taught to understand both the ecosystem's components and the interrelationship between organisms and the environment (MOE, 2015). To this end, teachers divide the science class into ecosystem components and interactions between ecosystem components. Ecosystem-related content's importance is further highlighted by its suitability for teaching systems thinking (Evagorou et al, 2009; Lee et al., 2019), which is emphasised as a prerequisite for functioning effectively and responsibly in a complex world (Arndt, 2006; Eilam, 2012; Jacobson & Wilensky, 2006).

Theoretical Background

Taught Curriculum and Learned Curriculum

The interaction between teachers and students facilitates the teaching–learning process in class. Taught curriculum refers to the process whereby teachers practice in class by integrating school education's needs, expectations, and intentions with students' situations and needs (Karabacak & Kürüm-Yapıcıoğlu, 2020). Meanwhile, learned curriculum refers to students' actual learning in class, with the learned content residing within their cognitive structures (Amineh & Asl, 2015; Glatthorn, 2000).

Students remember their learning and, when necessary, recall and recognise it (May et al., 2013). Assessing whether students remember and retrieve their learning helps ascertain whether learners have effectively learned the taught concepts (Jensen, 2005). Therefore, analysing learners' memories is one means to comprehend the cognitive structure that learners have learned and, arguably, to provide clues for deriving and understanding learning outcomes (Schwartz et al., 2011).

Examining retrieved memory helps ascertain the classroom learning that the learner remembers and the organisation and structuring of their knowledge into cognitive structures. Notably, SNA is employed to determine these learners' cognitive structures. Specifically, it can demonstrate these structures' organisation by identifying the connections between concepts within them (Kenett & Faust, 2019; Koponen & Nousiainen, 2014).

Learning occurs when students construct their own concepts based on the teacher's classes (Earl, 2013). Therefore, taught and learned curricula are interconnected, with any discrepancy between them precipitating problems in achieving class goals (Blank et al., 2001; McGehee & Griffith, 2001; Porter & Smithson, 2002). Therefore, analysing the kind of conceptual structure used by the teacher and that employed by the student is necessary, as is examining the alignment between the taught and learned curricula.

Ecosystem-related Contents in the Republic of Korea's Curriculum

This study's research subject was the ecosystem-related content in the Republic of Korea's curriculum. This content specifically referred to the class called 'Ecosystem Components'—taught in the 5th and 9th grades. The 5th-grade science curriculum aims to facilitate an understanding of the ecosystem, including living things and abiotic environmental factors influencing their lives. Accordingly, the relationship between living things and the environment is taught through examples of environmental factors (e.g., light, water, and temperature) that impact living things' lives and how they adapt to the environment.

In the 9th-grade integrated science curriculum, the 'Ecosystem and Environment Class' is taught. This class aims to facilitate an understanding of the ecosystem's components (including humans), the mutual relationship between organisms and the environment, and the necessity of preserving the ecosystem. Subsequently, cases of ecosystem balance and environmental changes impacting the ecosystem are investigated (MOE, 2015). This study selected the ecosystem's components and interactions between organisms and the environment as its research subjects.

Research Aim and Research Questions

Teaching and learning are interconnected, and the alignment between them is a very important measure for achieving the learning objectives. Therefore, the purpose of this study was to analyse the alignment between the taught curriculum and the learned curriculum from a conceptual perspective, and to suggest implications

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for teaching-learning strategies. To this end, this study attempted to compare the concepts that teachers use to teach, the concepts that students acquire through learning, and the concepts that they remember over time by structuring them into a concept network.

Therefore, this study aimed to analyse the concept networks taught by teachers and those learned by students regarding ecosystem-related content taught in upper secondary schools. This content is divided into ecosystem components and interactions between ecosystem components. Specifically, the following networks were analysed: the teacher's key teaching concept, the student's key learning concept, and the connection concept networks. That is, this study analysed the concept network that teachers teach concerning the ecosystem-related content and the resultant concept network that students learn. The research problem for this study is as follows.

What are the differences between teachers' teaching concept networks and students' learning concept networks in relation to the contents of the ecosystem composition of upper secondary school?

Research Methodology

Design

This study was designed to compare teachers' teaching concepts and students' learning concepts related to ecosystem content using network analysis in upper secondary schools in the Republic of Korea. Network analysis is an objective and scientific research method that complements the limitations of qualitative research methods that analyse the teaching and learning process in existing schools (Lee & Jeong, 2019).

The teaching concept network visualized the concepts used by teachers by recording the teachers' classes related to ecosystem contents. The student learning concept network visualized the concepts answered by students as a network using a learning memory questionnaire.

In integrated science in the Republic of Korea, ecosystem-related content is presented in the 'Ecosystem and Environment' unit, which is divided into two topics: 'Ecosystem Components' and 'Interactions between Ecosystem Components.' Each topic was conducted for 50 minutes, totalling 100 minutes. The class is conducted as a teacher-centred class, where the teacher primarily explains the material to the students. The actual class was conducted from October to December 2024 in accordance with the curriculum progress plan of the school to which the participants belonged. The content of the class was recorded and videotaped with the teacher's consent. The students' learning concepts through the class were collected through a learning memory questionnaire immediately after the class and four weeks after the class.

Participants

To analyse the network of teachers' teaching concepts and students' learning concepts regarding the ecosystem taught in upper secondary schools in the Republic of Korea, teachers and students from three upper secondary schools in a metropolitan city with a population of over 2.8 million were selected as participants. The academic achievement levels of students in the selected upper secondary schools correspond to those of students in the upper secondary schools in the Republic of Korea. This study's purpose, significance, and method were explained to the teachers and students, all of whom agreed with the same. The students were asked to respond to the questionnaire voluntarily.

All teachers were female, with their teaching experience ranging from 4 to 10 years. The study sample included 298 tenth-grade students. This is because all students taught by the subject teachers were sampled in order to analyse reliable learning concept networks. A large number of texts increases the reliability of the analysis results. The final analysis only included students who completed the questionnaires immediately after class and the follow-up test conducted four weeks later. Students who listed only concepts were excluded from the analysis. Consequently, the final number of students analysed was as follows: 85 students (43 male, 42 female) for the 'Ecosystem Components' class and 71 students (30 male, 41 female) for the 'Interactions between Ecosystem Components' class. At this time, when the sample size for semantic network analysis exceeds 15, it can be considered a sufficient sample based on evidence showing a high correlation of more than 90% with the population (Lim & Lee, 2013).

According to Article 2 of the Elementary and Secondary Education Act and Article 2 of the Higher Education Act of the Republic of Korea, research related to practical work within the scope of the school curriculum is subject to research ethics exemption (KoNIBP, 2018). Before conducting this study, measures such as obtaining consent

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were taken after notifying the school, students, and parents that the personal information of participants would not be collected or recorded.

Ecosystem Classes

Classes were conducted based on the curriculum progress plan of the school to which the participants belonged. The class covered ecosystem components and the interactions between these components; the classes were conducted for 50 minutes each, totalling 100 minutes.

The content of the 'Ecosystem Components' class aims to facilitate the understanding of the meaning and examples of biotic and abiotic factors that constitute the ecosystem. The teacher divided biotic factors into producer, consumer, and decomposer, and levels, such as individual, population, and community, explaining the meaning of each and illustrating them with examples of living things commonly seen around us. For abiotic factors, the teacher first explained the meaning and then provided explanatory examples, such as soil, air, and water.

The content of the 'Interactions between Ecosystem Components' class aims to facilitate an understanding of how biotic and abiotic factors constituting an ecosystem impact each other. The teacher utilised varied examples to explain the effects of biotic factors on abiotic factors and those of abiotic factors on biotic factors, with the former illustrated using examples of plants and animals.

Questionnaire

A learning memory questionnaire was used to collect data and describe students' learning concepts related to ecosystem components and interactions between these components. The learning memory questionnaire used a questionnaire that was verified in previous studies (Chun et al., 2024; Lim et al., 2020). The learning memory questionnaire was modified and supplemented to fit the subject of this study, 'Ecosystem Components' and 'Interactions between Ecosystem Components' classes. For this, two seminars were held with two biology education experts, one doctoral student, and two master's students. The questionnaire—created using Google Forms—comprised learning topics, learning objectives, writing methods, and writing examples.

Data Collection and Analysis

First, the class conducted by the teacher was recorded and videotaped to analyse the concept network taught by the teacher. The collected data were transcribed into a text file (.txt). Subsequently, the students were required to complete two questionnaires to determine their learning concepts. The questionnaires were administered via a Google form on a tablet PC under the teacher's supervision and took approximately 10 minutes to complete. Thereafter, the responses to the questionnaires were also transcribed as a text file (.txt).

The collected data regarding the concepts taught by teachers and those learned by students were utilised to extract concepts using Net Miner 4.0. A dictionary of exclusion words was created to remove non-scientific concepts from the extracted concepts; further, a thesaurus was created to integrate words with similar meanings (Kim et al., 2023; Yun & Park, 2018). Based on this process, 56 concepts were selected.

To ensure that only the concepts essential for learning 'Ecosystem Components' and 'Interactions between Ecosystem Components' were included among the selected concepts, concept validity was reviewed by two biology education experts and four current life science teachers. These life science teachers had over 10 years of teaching experience, while two had master's degrees and two had doctoral degrees. Consequently, 45 concepts were finally selected.

For the concepts finally selected, the key concept and connection concept networks were analysed as 1-mode and 2-mode, respectively. The key concept and connection concept networks involved concepts with a frequency rate of 30% or higher, targeting concepts that both teachers and students primarily presented. Figure 1 depicts an example of a network visualising all the concepts taught by teachers in class. This study elucidated the key concept and connection concept networks.

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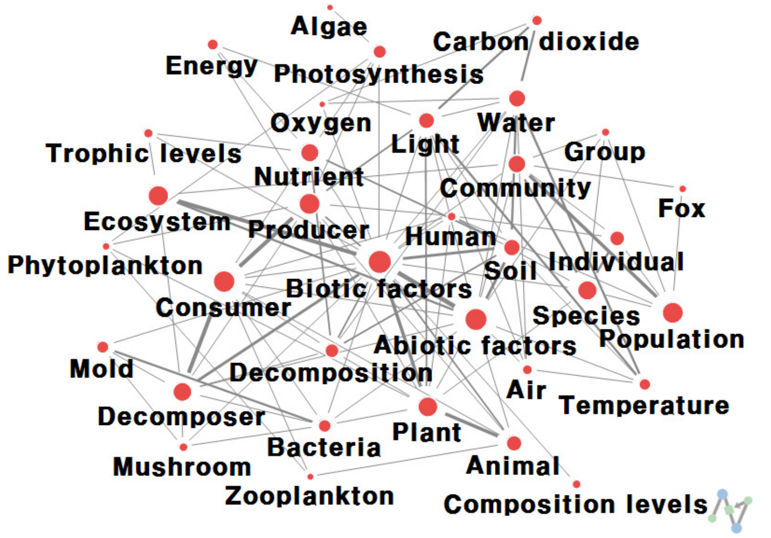
Figure 1

Example of a Network of All Concepts Taught by Teachers in the 'Ecosystem Components' Class



Research Results

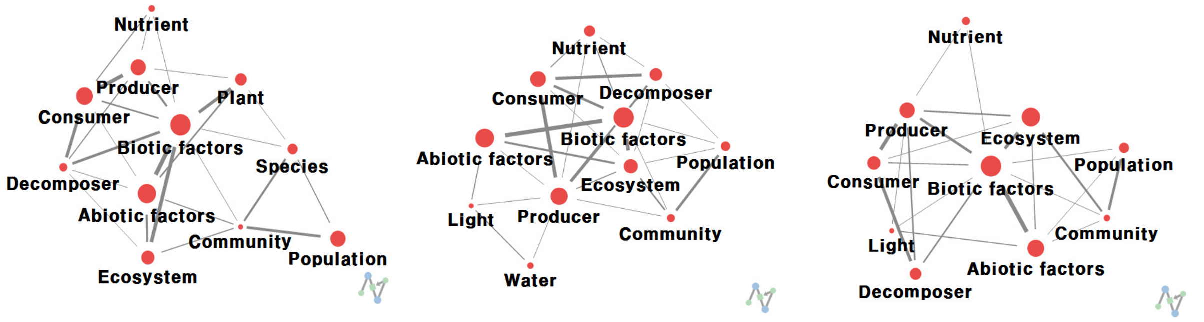
Network of Key Concepts

Ecosystem Components

Figure 2 depicts the networks of key concepts for the ecosystem components class as follows: (a) teaching concepts, (b) learning concepts after class, and (c) learning concepts at follow-up. The total number of teaching concepts is 11 (Figure 2a). The teaching concept network centres around 'Biotic factors', 'Abiotic factors', and 'Community'. 'Biotic factors' are connected to 'Producer', 'Plant', 'Community', and so on. 'Abiotic factors' are connected to Ecosystem', 'Plant', 'Consumer', and so on. Finally, 'Community' is connected to 'Species', 'Population', 'Ecosystem', and so on.

Figure 2

Networks of Key Concepts for Ecosystem Components



a) Teaching concepts b) Learning concepts after class c) Learning concepts at follow-up

The total number of learning concepts after class is 11 (Figure 2b). The learning concept network after class centres around 'Biotic factors', 'Producer', and 'Ecosystem'. 'Biotic factor' is connected to 'Consumer', 'Nutrient', and

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'Ecosystem'. 'Producer' is connected to 'Biotic factors', 'Light', and 'Community'. Finally, 'Ecosystem' is connected to 'Biotic factors', 'Abiotic factors', and 'Water'.

Ten learning concepts are observed at follow-up (Figure 2c). The learning concept network at follow-up centres around 'Biotic factors', 'Community', and 'Producer'. 'Biotic factors' is connected to 'Producer', 'Nutrient', and 'Consumer'. 'Community' is connected to 'Population', 'Ecosystem', and 'Species'. Finally, 'Producer' is connected to 'Biotic factors', 'Ecosystem', and 'Nutrient'.

Most key concepts presented in teaching concepts, learning concepts after class, and learning concepts at follow-up were the same, but some differed. The concepts of 'Light' and 'Water'—examples of abiotic factors—appeared in the student's learning concept network immediately after class, but not in the teacher's teaching concept network or the student's learning concept network at follow-up. The students' concept networks immediately after and four weeks after class exhibited a higher relative frequency of 'Ecosystem' and were connected to more concepts than the teacher's teaching concept network. This was believed to be the result of students integrating the concepts learned in class based on their holistic understanding of the ecosystem.

Interactions between Ecosystem Components

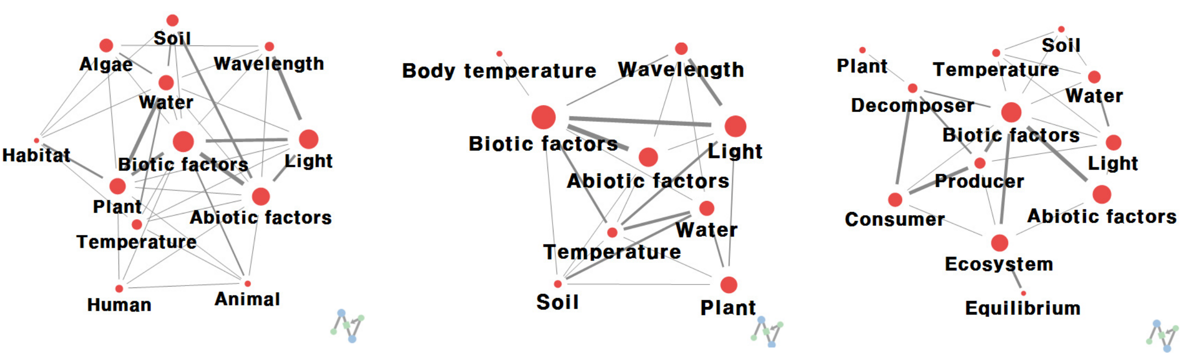
The networks for teaching concepts, learning concepts after class, and learning concepts at follow-up regarding 'Interactions between Ecosystem Components' are analysed (Figure 3). The total number of teaching concepts in the key concept network is 12 (Figure 3a). The teaching concept network centres around 'Biotic factors', 'Abiotic factors', and 'Water'. 'Biotic factors' are connected to 'Plant', 'Algae', and 'Abiotic factors'. Further, 'Water' is connected to 'Plant', 'Habitat', and 'Temperature'. Finally, 'Abiotic factors' are connected to 'Light', 'Soil', and 'Plant'.

The total number of learning concepts after class in the key concept network is 11 (Figure 3b). The key concept network for learning concepts after class centres around 'Biotic factors', 'Temperature', and 'Water'. 'Biotic factors' is connected to 'Poikilotherm', 'Body temperature', and 'Wavelength'. 'Temperature' is connected to 'Animal', 'Plant', and 'Biotic factors'. Finally, 'Water' is connected to 'Soil', 'Plant', and 'Animal'.

Twelve learning concepts are observed at follow-up in the key concept network (Figure 3c). The key concept network for learning concepts at follow-up centres around 'Biotic factors', 'Light', and 'Producer'. 'Biotic factors' is connected to 'Producer', 'Consumer', and 'Temperature'. 'Light' is connected to 'Producer', 'Biotic factors', and 'Temperature'. Finally, 'Producer' is connected to 'Ecosystem', 'Consumer', and 'Light'.

In the key concept network for teaching and learning concepts after class, 'Plant' was connected to various concepts, such as 'Biotic factors' and 'Abiotic factors', thereby forming a complex mesh. However, in the network for learning concepts at follow-up, 'Plant' was connected only to 'Oxygen' and 'Decomposer', thus demonstrating a linear form. This indicated that students effectively remember the relationship between 'Plant' and other concepts taught by the teacher immediately after class; however, most relationships between 'Plant' and other concepts were forgotten after four weeks.

Figure 3
Networks of Key Concepts for the 'Interactions between Ecosystem Components'



a) Teaching concepts b) Learning concepts after class c) Learning concepts at follow-up

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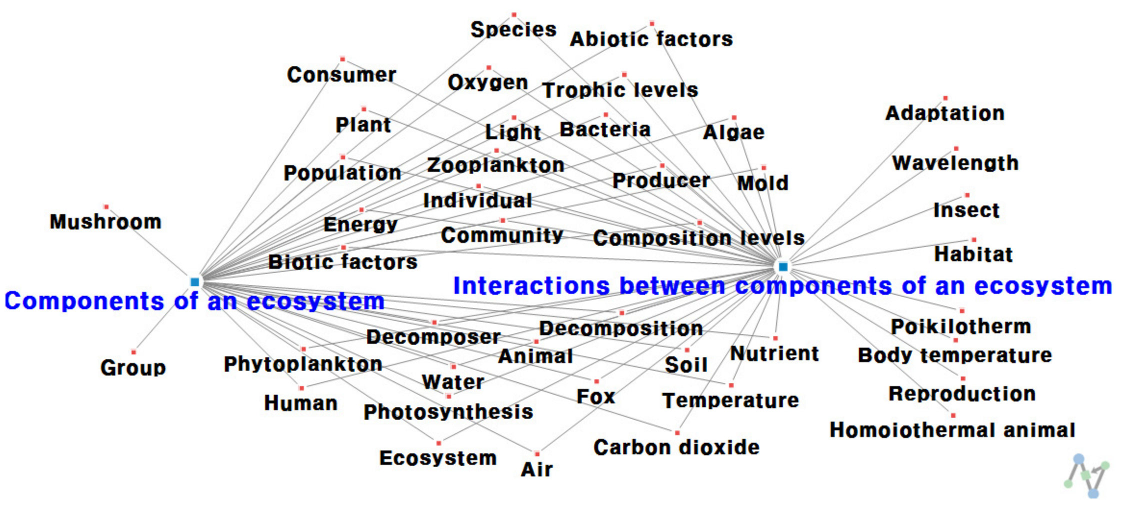
Connection Network

Connection Network between Classes

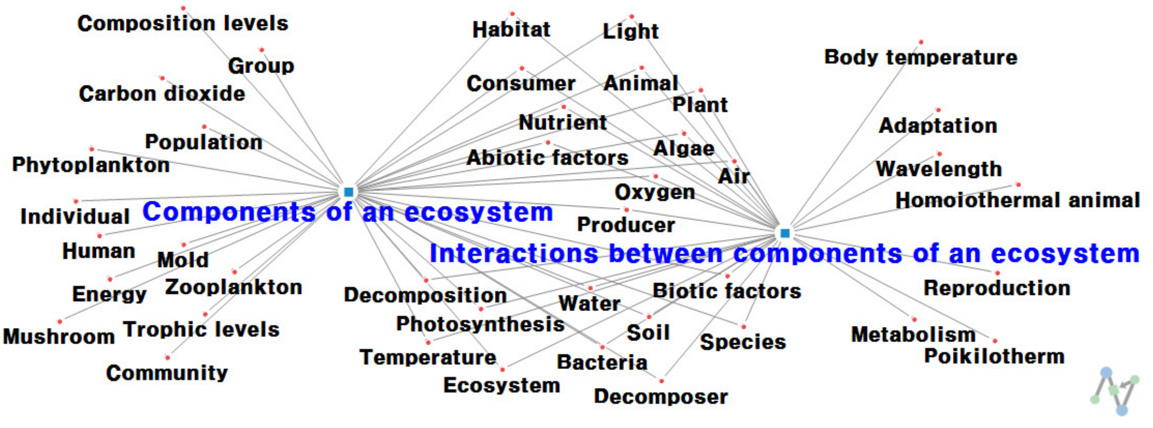
The connection networks of the concepts presented in the 'Ecosystem Components' and 'Interactions between Ecosystem Components' classes are analysed (Figure 4). In the connection network of teaching concepts (Figure 4a), the number of concepts utilised in both classes is 32, including 'Biotic factors', 'Abiotic factors', 'Nutrient', 'Air', and 'Energy'. The number of concepts employed only in the 'Ecosystem Components' class is two, namely, 'Group' and 'Mushroom'. Finally, the number of concepts utilised only in the 'Interactions between Ecosystem Components' class is six, including 'Body temperature' and 'Adaptation'.

Analysing the connection network for learning concepts after class (Figure 4b) reveals 25 commonly appearing concepts, including 'Producer', 'Consumer', 'Decomposer', 'Population', and 'Ecosystem'. Eight concepts appear only in the 'Ecosystem Components' class, including 'Zooplankton', 'Phytoplankton', 'Composition levels', 'Trophic levels', and 'Mold', while six concepts appear only in the 'Interactions between Ecosystem Components' class, including 'Reproduction', 'Metabolism', 'Body temperature', and 'Poikilotherm'.

Figure 4
Connection Networks Between Classes



a} Teaching concepts



b) Learning concepts after class

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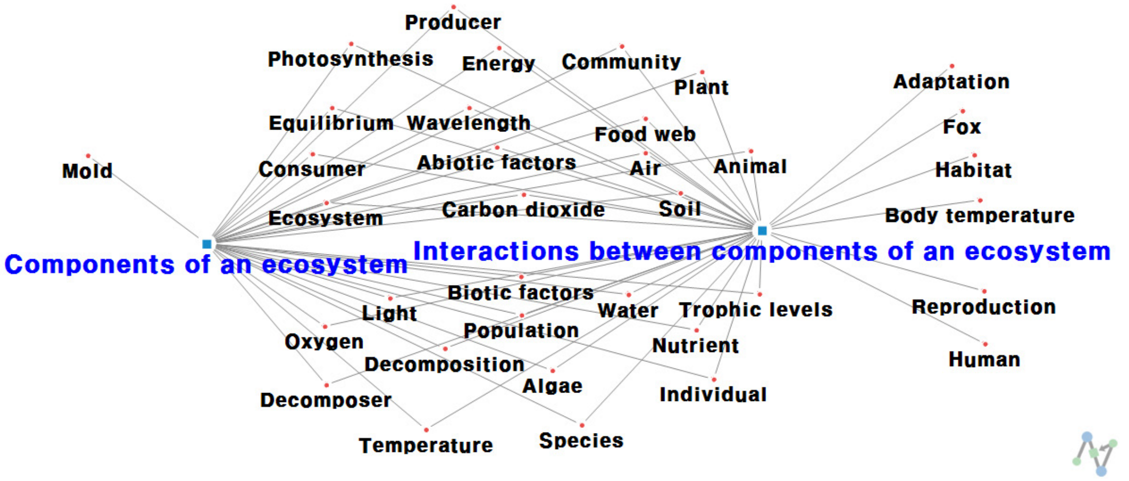

c) Learning concepts at follow-up

In the connection network for learning concepts at follow-up (Figure 4c), 28 commonly appearing concepts are observed, including 'Food web', 'Individual', 'Temperature', 'Equilibrium', and 'Carbon dioxide'. Seven concepts appear only in the 'Interactions between Ecosystem Components' class, including 'Human', 'Body temperature', 'Poikilotherm', 'Fox', and 'Adaptation', while one concept appears only in the 'Ecosystem Components' class, namely, 'Mold'.

Connection Network between Teaching Concepts, Learning Concepts after Class, and Learning Concepts at Follow-up for Each Class

In the 'Ecosystem Components' class, the connection networks for teaching concepts, learning concepts after class, and learning concepts at follow-up are analysed (Figure 5a). The commonly presented concepts are 26 in total, including 'Biotic factors', 'Abiotic factors', 'Nutrient', 'Plant', and 'Decomposer'. The number of concepts that appeared only in teaching and learning concepts after class is seven, including 'Mushroom', 'Composition levels', and 'Bacteria'. By contrast, the concept presented only in the teaching concepts is 'Fox', while that presented only in the learning concepts after class is 'Habitat'. Finally, the concepts presented only in the learning concepts at follow-up are 'Equilibrium', 'Food web', and 'Wavelength'.

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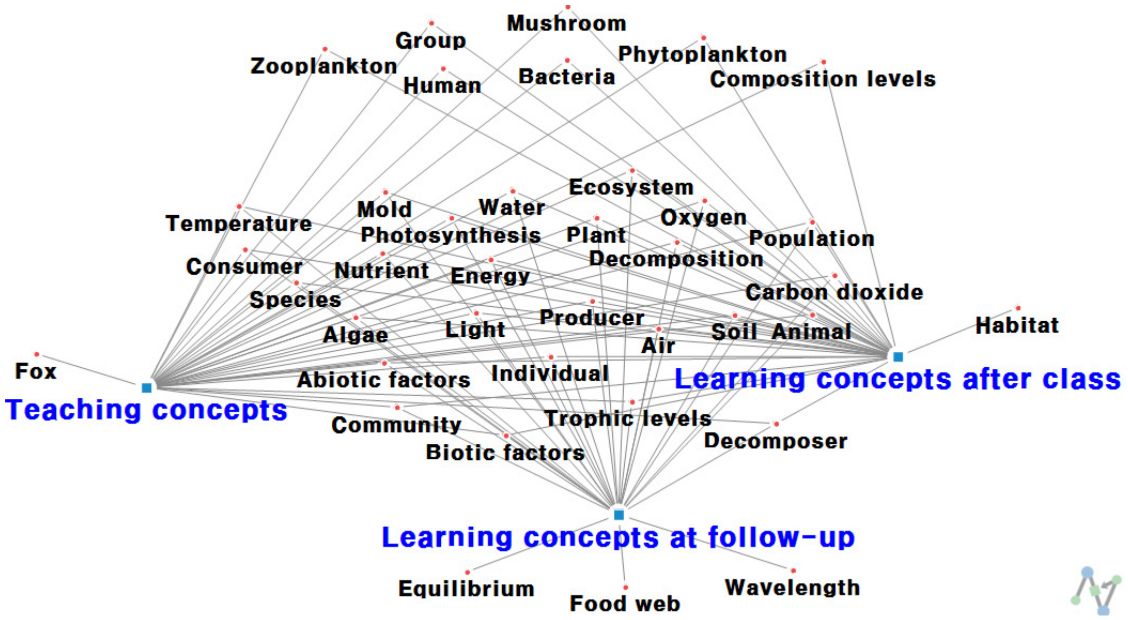
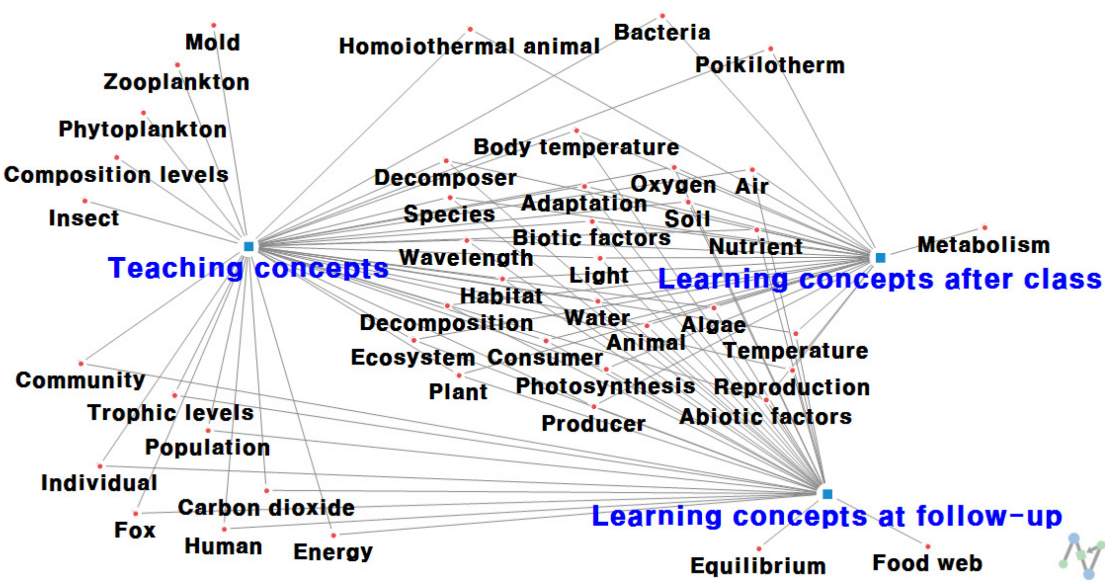
Figure 5

Connection Networks Between Teaching Concepts, Learning Concepts After Class, and Learning Concepts at Follow-up for Each Class



a) 'Ecosystem Components' class



b) 'Interactions between Ecosystem Components' class

In the 'Interactions between Ecosystem Components' class (Figure 5b), the concepts commonly presented in teaching concepts, learning concepts after class, and learning concepts at follow-up include 'Biotic factors', 'Abiotic factors', 'Wavelength', 'Body temperature', and 'Algae', among others, totalling 24 concepts. The concepts commonly presented in teaching and learning concepts after class are 'Bacteria', 'Homoiothermal animal', and

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'Poikilotherm' for three concepts. Further, the concepts commonly presented in teaching and learning concepts at follow-up are 'Population', 'Carbon dioxide', and so on, for eight concepts. By contrast, the concepts presented only in the teaching concept are 'Mold', 'Zooplankton', 'Phytoplankton', 'Composition levels', and 'Insects', while the concept presented only in the learning concepts after class is 'Metabolism'. Finally, the concepts presented only in the learning concepts at follow-up are 'Equilibrium' and 'Food web'.

Noteworthily, teaching concepts, learning concepts after class, and learning concepts at follow-up were generally similar. However, in the learning concepts at follow-up, the teacher presented a concept called 'Food web', which was not taught in the 'Ecosystem Components' class but appears in a follow-up class called 'Ecosystem Equilibrium' after learning all the contents. This concept's incorporation demonstrated that students connect concepts learned in class with concepts learned later.

Discussion

This study examined the networks for teaching concepts, learning concepts after class, and learning concepts at follow-up vis-à-vis ecosystem-related content in upper secondary schools in the Republic of Korea. The key concepts taught by the teachers and those learned by students were similar (Figure 5), whereas the structures of the teaching and learning concept networks differed—consistent with previous findings (Chun et al., 2024; Lim et al., 2020).

In the 'Ecosystem Components' class, the teacher focused on teaching biotic factors (Figure 2a). Immediately after the class, students formed a network that included both 'Biotic factors' and 'Abiotic factors' (Figure 2b); however, four weeks later, they formed a network centred on 'Biotic factors' (Figure 2c). Additionally, in the 'Interactions between Ecosystem Components' class, the teacher explained how abiotic factors impact animals and plants. Immediately after the class, students formed a network centred on the 'effects of abiotic factors on plants'; nevertheless, four weeks later, they could not form a network centred on biotic factors and the relationship between the types of abiotic factors and plants.

In classes incorporating inquiry activities, teachers provided concept-centred explanations, but students formed networks including concepts related to the inquiry (Lim, Kim & Kim, 2024). In classes not incorporating inquiry activities, structures were formed related to concepts such as 'biological factors'. Furthermore, students could not clearly distinguish between subtopics and form concept networks (Chun et al., 2024)—consistent with Case et al.'s (1996) finding that students' development of concept structures is impeded by unclear subtopic distinction.

The teacher presented a large number of concepts while conducting the class. Among the concepts utilised to explain examples of interactions between ecosystem components, 'Zooplankton', 'Phytoplankton', 'Insect', and 'Mold' were not retained by the students immediately after and four weeks after the class (Figure 5b). This finding is attributable to the teacher's belief that they must teach a large number of concepts to the students (Jeong et al., 2010).

The teacher repeatedly used the concepts in class. Notably, 32 concepts appear simultaneously in the classes of the 'Ecosystem Components' and 'Interactions between Ecosystem Components' classes (Figure 4). This is primarily because biology is the science of living systems, is inherently hierarchical, and comprises varied subsystems (Ginsburg et al., 1998; Momsen et al., 2022). Seemingly, as the teacher's explanation did not differentiate between the two classes' concepts and repeatedly overlapped, the students could not clearly distinguish between them.

After four weeks, the students' follow-up concepts incorporated concepts that were not explained in class. The concepts that emerged four weeks after class were 'Equilibrium' and 'Food web'—attributable to the content focusing on ecosystem equilibrium, which was taught after the lesson on the 'Interactions between Ecosystem Components' class. This finding indicates that students' subsequent learning influences their prior learning, resulting in them reconstructing their learning content (Noddings, 1995; Wood, 1995). Therefore, as subsequent learning influences the conceptual structure of prior learning, teachers must explain its connection to prior learning during follow-up classes.

Conclusions and Implications

This study compared the networks of teaching and learning concepts pertaining to the ecosystem-related content in upper secondary schools. This study's conclusions are as follows: First, teachers and students predominantly share the same concept of the entire ecosystem; however, the detailed structures of the key concept networks differ. Regarding the ecosystem's components, teachers primarily explained them in terms of biotic elements, whereas students learned them as a mixture of biotic and abiotic elements. Teachers explained the relationship among

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the concepts of 'Species', 'Community', and 'Population' by connecting all three, whereas students predominantly understood them in terms of the concepts of 'Community' and 'Population'.

Second, the teacher repeatedly utilised the concepts in consecutive classes, rendering it challenging for students to clearly distinguish between the two classes' concepts. The teacher simultaneously employed 32 concepts in the lessons on the 'Ecosystem Components' and 'Interactions between Ecosystem Components' classes, with only two and eight concepts appearing in each class, respectively. Seemingly, students could not clearly distinguish between the concepts covered in these two classes because of similar conceptual statements.

Third, the follow-up learning content influenced the pre-learning. The concepts of 'Carbon dioxide', 'Population', and 'Trophic levels' were presented only in the 'Ecosystem Components' class immediately after the class; however, four weeks later, these concepts connected the two classes. Moreover, the concepts of 'Equilibrium' and 'Food web' appeared four weeks after the class.

In this study, the teachers' teaching concept and the students' learning concept were compared using the concept network to analyse the effective utilization of the concept in the class from the conceptual perspective. In order to complete an effective teaching-learning process, the structural difference between the teachers' teaching concept and the students' learning concept should be reduced. To this end, it is necessary to present concepts in a structured manner by grouping them so that students can easily understand the connection between concepts. rather than repeatedly using concepts. It is thought that presenting concepts clearly distinguished from each In addition, it is necessary to present concepts clearly distinguished from each topic other will help clarify the distinction between follow-up learning and prior learning, that is, the relationship between classes, and will have a positive effect on structuring concepts in students' cognitive structures.

Students learn through the process of reconstructing the learning content presented by the teacher in their own cognitive structures and remembering them. To achieve the educational goal, teachers must consider how students understand and reconstruct concepts, as well as how to organize and conduct classes effectively. Future studies need to analyse how various variables, such as different teaching methods (e.g., inquiry-based classes versus teacher-centred classes) and learner characteristics, affect the learning concept network.

Declaration of Interest

The authors declare no competing interest.

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EFFECTS OF BIOMIMICRY-ENRICHED ENGINEERING DESIGN-BASED TEACHING ON STUDENTS' ASSOCIATION WITH DAILY LIFE, STEM ATTITUDE, AND BIOMIMICRY ATTITUDE IN SOUND AND ITS PROPERTIES UNIT

Derya Kaltakci-Gurel,
Esra Gokce

Abstract. *This study examined the effects of biomimicry-enriched engineering design-based teaching on sixth graders' daily life associations, STEM attitudes, and biomimicry attitudes in the "Sound and Its Properties" unit. A pre-test post-test quasi-experimental design was used, with four classes randomly assigned to experimental and control groups. The study involved 109 sixth graders in Türkiye. The experimental groups received biomimicry-enriched engineering design-based teaching for 22 hours, while the control groups followed the existing curriculum. The Association with Daily Life Test (ADLT) in the sound topic, Biomimicry Attitude Scale (BAS), and STEM Attitude Scale (SAS) were administered as pre-tests and post-tests to collect data. The post-test scores of the students' association with daily life, biomimicry attitude, and STEM attitude were compared using Multivariate Analysis of Covariance (MANCOVA) when their pre-test scores were controlled. The findings of the study revealed that the students in the experimental group had significantly higher levels of association with daily life, STEM attitude, and biomimicry attitude compared to those in the control group, with the most substantial impact on association with daily life in the sound topic.*

Keywords: *biomimicry-enriched teaching, engineering design-based teaching, biomimicry attitude, STEM attitude, association with daily life.*

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Introduction

Among the primary problems in science education, a plethora of issues are listed such as: an overly content-heavy curriculum, the inability to connect scientific knowledge with daily life, insufficient connection between disciplines and topics, the inability of students to transfer concepts to different situations or environments, insufficient emphasis, and inadequacies in answering students' questions of "why do I need to learn this?" Previous studies (Demircioğlu et al., 2009; Gilbert, 2006; Gürel, 2017; Pilot & Bulte, 2006) asserted that various methods and approaches are needed to address these problems encountered during the teaching-learning process, to cultivate scientific literacy in students, and to enable them to acquire higher-order thinking skills. It is emphasized that connecting science lessons to daily life is essential for this purpose (Gilbert, 2006). Pilot and Bulte (2006) and Kaltakci-Gurel (2018) argued that when science education is relevant to students' lives and interests, their comprehension of the subject improves. Education systems worldwide are increasingly focusing on equipping students with problem-solving skills and interdisciplinary approaches to science and technology. STEM (Science, Technology, Engineering, and Mathematics) education aims to integrate these disciplines to enhance students' cognitive abilities and prepare them for real-world challenges (Aksoy et al., 2023; Aydin-Gunbatar et al., 2018; Rehmat et al., 2024). Within this educational paradigm, innovative teaching strategies such as engineering design-based learning have been introduced to engage students actively in science education (Fortus et al., 2005; Mohd Shahali et al., 2016; Wendell & Lee, 2010). Recent studies suggest that incorporating biomimicry—a practice that draws inspiration from nature to solve human challenges—can enhance students' learning experiences in

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STEM fields by fostering creativity and innovation (Avcı, 2019; Gardner, 2012; Pauls, 2017). Biomimicry allows students to apply scientific knowledge in practical contexts, encouraging the association of scientific concepts with everyday life. The current study aims to examine the effectiveness of biomimicry-enriched engineering design-based teaching as an innovative approach relevant to real-life situations and students' attitudes. The "sound and its properties" unit was selected as the science topic because, while previous studies have found sound to be a challenging concept for learners, there is limited research on effective methods for teaching students about sound and its relevance to their daily lives (Aksoy et al., 2023; Eshach & Schwartz, 2006; Faletič, 2023).

Biomimicry in Science Education

In her 1997 book, Biomimicry: Innovation Inspired by Nature, Janine Benyus (1997) introduced a new approach to learning from nature. The term biomimicry was derived from the Greek words bios (life) and mimesis (imitation). It is an interdisciplinary approach that seeks inspiration from nature's patterns and strategies to solve human challenges. This approach goes beyond mere imitation; it involves understanding the core principles of natural processes and adapting them to human engineering, design, and innovation. Biomimicry has been instrumental in revolutionizing various sectors, including medicine, architecture, materials science, and engineering (Sedira et al., 2024; Yeter et al., 2023). Biomimetic innovations in these scientific and technological disciplines have led to advancements such as self-cleaning surfaces inspired by lotus leaves, energy-efficient building designs that mimic termite mounds, and high-performance adhesives modeled after gecko feet. Beyond its practical applications, biomimicry is increasingly being incorporated into education, as it provides a unique way to engage students by linking biology and engineering with real-world applications. The integration of biomimicry into educational curricula helps bridge the gap between theoretical knowledge and real-world applications, making biomimicry a highly effective and engaging approach for students. Several studies in the literature emphasize the importance of teaching and teaching with biomimicry to foster critical thinking, creativity, innovation, association with daily life, and problem-solving skills (Ersanlı, 2016; Gardner, 2012; Jacobs et al., 2022; Kandemir et al., 2022; Qureshi, 2022; Rehmat et al., 2024; Savran Gencer et al., 2020; Sumrall et al., 2018). These studies mainly focused on students' biomimicry perceptions and awareness (Sağır et al., 2022; Sürgü & Güneş, 2022; Velioğlu & Yakişan, 2022; Yakişan & Velioğlu, 2019), how students conceptualize and engage in biomimicry (Qureshi, 2022; Yeter et al., 2023), development of biomimicry activity and teaching approach (Canbazoğlu Bilici et al., 2021; Coban & Coştu, 2023; Savran Gencer et al., 2020; Sumrall et al., 2018), associating biomimicry examples with daily life (Ersanlı, 2016; Kandemir et al., 2022). However, the number of studies in teaching science concepts with biomimicry is still relatively small. Some of the approaches involving biomimicry, such as inquiry-based learning (Qureshi, 2022), project-based learning (Jatsch et al., 2023), and engineering design-based teaching (Canbazoğlu Bilici et al., 2021; Coban & Coştu, 2023; Pauls, 2017; Rehmat et al., 2024) are proposed to help students not only understand scientific concepts but also apply these concepts to solve complex, real-world challenges. By integrating biomimicry into these educational strategies, educators can inspire the next generation of thinkers and innovators, particularly in STEM fields, while promoting sustainability and environmental stewardship.

Engineering Design-Based Teaching

Recent studies have highlighted the importance of STEM education in fostering global competitiveness. The need to equip individuals with strong STEM skills to meet the demands of the modern workforce is emphasized by several studies (Aydin-Gunbatar et al., 2018; Bissaker, 2014; National Center for Science and Engineering Statistics [NCSES], 2023; National Research Council [NRC], 2012; Ring et al., 2017). However, employers often struggle to find employees with the ability to apply scientific and technological knowledge to develop innovative solutions to real life problems. STEM education has emerged as a promising approach to address this challenge. By combining science, technology, engineering, and mathematics, integrated STEM instruction focuses on solving real-world problems through practical applications (Aydin-Gunbatar et al., 2018; Korur et al., 2017). The integration of these fields should be grounded in engineering design and problem-solving, as emphasized by the National Research Council [NRC] (2012) and Next Generation Science Standards [NGSS] (2013). Engineering design is a key component of effective STEM education. In this respect, previous studies (Apedoe et al., 2008; Aydin-Gunbatar et al., 2018; Burrows et al., 2014; Delen & Yuksel, 2022; Kolodner, 2002) emphasized the importance of incorporating engineering design into science teaching. Through engineering design processes, students engage in activities such as analyzing situations, collecting information, brainstorming solutions, developing models, and testing

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prototypes (NRC, 2012; NGSS, 2013). Studies have also shown that design-based learning can enhance student performance and attitude by engaging students in active learning and problem-solving, making it a key factor in the success of integrated STEM education as well as fostering engineering and other higher order skills (Apedoe & Schunn, 2013; Capobianco et al., 2015; Doppelt, 2009; Korur et al., 2017; Mehalik et al., 2008; Silk et al., 2009). The success of integrated STEM education depends on innovative applications and practices. Ring et al. (2017) and NRC (2014) highlight the need for new approaches to effectively implement integrated STEM education and engineering design processes. By adopting these strategies, educational systems can better prepare students for the challenges of the 21st century. Hynes et al. (2011), Marulcu and Sungur (2012), and National Aeronautics and Space Administration [NASA] (2023) proposed several frameworks for integrating science and engineering through engineering design-based teaching. This study innovated upon the existing engineering design process cycles by integrating biomimetic applications. As depicted in Figure 1, this novel process was employed in experimental group activities in the current study.

Integration of Biomimicry and Engineering Design-Based Teaching

Combining biomimicry with engineering design-based teaching creates a powerful educational approach that encourages innovation and sustainability in problem-solving. By using biomimicry as a central theme in engineering design-based teaching, students learn to approach problems systematically, considering both functionality and environmental impact. In the integration of biomimicry and engineering designs, biomimicry can be approached from two primary perspectives: bottom-up and top-down (Aziz & El Sherif, 2016), which can also be used for educational purposes. The first bottom-up perspective involves applying biology to design, where a biological phenomenon provides a new solution to a design problem. The second top-down approach is design-to-biology, where a design problem is identified, the core function is defined, and then observations are made of how organisms and ecosystems fulfill this function.

Engineering design-based activities that incorporate the biomimicry approach affect students' understanding of biomimicry, creative thinking and help them develop different perspectives on nature and gain a positive attitude towards the idea of biomimicry (Canbazoğlu Bilici et al., 2021; Coban & Coştu, 2023; Gardner, 2012; Pauls, 2017). Engaging in engineering design activities based on these principles can further deepen their comprehension of biomimicry and its applications. Gardner (2012) highlighted the significance of design-based biomimicry activities that incorporate science content, particularly at the molecular and nanoscale levels, in promoting a deeper understanding of biomimicry. Gardner's study (2012) demonstrated that a biomimetic matching cards activity can effectively enhance students' understanding of biomimicry principles. In this activity, students were required to match cards depicting organisms with cards showcasing related technologies, fostering discussions about the innovation process used by researchers. In the study by Canbazoğlu Bilici et al. (2021), lower-secondary school students were tasked with designing eco-friendly vehicles inspired by nature that could help reduce air pollution. Through this activity, students learned about engineering design, biomimicry, air pollution, and the structural features of different organisms. The study suggests that incorporating biomimicry-based design activities into STEM classrooms can be a valuable learning experience for students. Similarly, Coban and Coştu (2023) sought to integrate biomimicry into science education for fifth-grade primary school students. The researchers developed a teaching approach incorporating a biomimicry design model and implemented it in a Turkish fifth-grade classroom. The approach involved introducing students to various organisms, explaining the concept of biomimicry, and guiding them through a nature-inspired design process. After completing the lessons, students created their own designs based on the studied organisms. The results indicated that the activities enhanced the participants' creativity. However, the study found that students primarily relied on information provided during the design process. This underscores the importance of a strong foundation of knowledge and practical experience to fully realize the potential of nature-inspired design. A rich learning environment that fosters students' curiosity and interest is proposed as essential for cultivating their creativity and innovation. In similar applications combining STEM and biomimicry, studies have concluded that students can develop innovative solutions to real-world problems by utilizing their imagination and applying the biomimicry approach in conjunction with engineering design principles (Alperen, 2020; Pauls, 2017; Savran Gencer et al., 2020; Yakişan & Velioğlu, 2019).

To sum up, biomimicry offers a unique way of bridging the gap between biology, engineering, and education. In general, it serves as a sustainable and innovative approach to solving real-world problems. In science education, it provides students with a creative and engaging platform to explore biological principles and their applications in technology and engineering. Finally, integrating biomimicry with engineering design-based teaching fosters

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a comprehensive learning experience that prepares students for the challenges of modern engineering while promoting sustainability and innovation.

Research Aim and Research Question

Innovative teaching methods are needed to help students develop problem-solving skills and find practical solutions to real-world challenges in everyday contexts. In this context, it was thought that teaching science with engineering design-based approaches would help students find practical solutions to their problems, develop their creative designs, and improve their ability to apply the design process. As stated in previous studies (Canbazoğlu Bilici et al., 2021; Gardner, 2012; Pauls, 2017; Savran Gencer et al., 2020), biomimicry activities offer an important opportunity to teach STEM (Science, Technology, Engineering, and Mathematics) fields with an integrated approach. By examining nature and producing creative solutions to encountered problems, developing these designs, and integrating them into engineering design practices, students can identify and be inspired by the solutions produced by other living things in nature while overcoming their own challenges. This approach has the potential to be groundbreaking and beneficial for students' learning as well as attitudes, and the present study is one of the pioneering experimental studies integrating biomimicry into engineering design in science education. While there has been growing interest in biomimicry in education, there is still limited research on its impact on students' attitudes towards STEM and their ability to relate scientific concepts to daily life. Existing studies have focused primarily on its use in high school and higher education, leaving a gap in understanding its effectiveness in primary and lower-secondary school settings. This study aimed to fill that gap by examining how sixth graders' attitudes towards STEM and biomimicry and their association of science with everyday experiences are influenced by biomimicry-enriched engineering design-based teaching. While this study is situated within a specific educational context, the challenges it addresses—fostering students' connection to daily life, enhancing STEM attitudes, and promoting innovative thinking through design—are universal concerns across diverse educational systems worldwide. Therefore, the insights gained from examining biomimicry-enriched engineering design-based teaching hold significant potential for global applicability and can inform pedagogical practices in various international settings.

Building on this framework, the present study examined the effects of biomimicry-enriched engineering design-based teaching on sixth-grade students' STEM attitudes, association with daily life in the context of the sound concept, and their biomimicry attitudes. Specifically, the study aimed to answer the following research question:

Is there a significant mean difference between the post-test scores of the experimental and control groups exposed to biomimicry-enriched engineering design teaching and conventional teaching on "sound and its properties unit" regarding attitudes towards biomimicry, association with daily life, and attitudes towards STEM, when the pre-test scores are controlled?

Research Methodology

General Background

In this study, a quasi-experimental design with a pretest-posttest control group was used. The experimental group received lessons with biomimicry-enriched engineering design-based applications, while the control group followed the existing curriculum for the sixth-grade "sound and its properties" unit. Pre- and post-tests were administered to both groups to assess changes in their associations with daily life, attitudes towards biomimicry, and attitudes towards STEM.

To ensure the equivalence of the groups before the intervention, a biomimicry awareness questionnaire (BAQ) was administered to all students. Based on the results, classes were randomly assigned to experimental and control groups. All groups took pre-tests one week before the implementation, the treatment was given in four weeks (22 lesson hours), and the study concluded with administering post-tests. Table 1 outlines the implementation steps of the quasi-experimental design in this study.

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Table 1
Symbolic Representation of Quasi-Experimental Design in Study [1]

Group	Matching	Pre- Test	Intervention	Post- Test
Experimental	BAQ	• pre-ADLT • pre-SAS • pre-BAS	Engineering design-based lesson plans enriched with biomimicry approach	• post-ADLT • post-SAS • post-BAS
Control	BAQ	• pre-ADLT • pre-SAS • pre-BAS	Existing/standard curriculum lesson plans	• post-ADLT • post-SAS • post-BAS

[1] BAQ: Biomimicry Awareness Questionnaire, ADLT: Association with Daily Life Test, SAS: STEM Attitude Scale, BAS: Biomimicry Attitude Scale

Participants

By a combination of purposive and convenience sampling methods, four intact classes were selected for this study. Two criteria were considered in selecting classes: first, the availability of the classes to the researcher, and second, teachers with at least two classes were selected to eliminate the instructor and researcher effects on internal validity. The sample for this study consisted of 109 sixth-grade students from a state elementary school in Ankara, Türkiye. Of these students, 59 were female (54.13%) and 50 were male (45.87%). Four classes were randomly assigned to experimental and control groups: two experimental groups and two control groups. Before the group assignment, a biomimicry awareness questionnaire (BAQ) was administered to all students. As there were no significant differences in BAQ scores among the classes, random assignment was used. The experimental group included 57 students (52.3%), and the control group included 52 students (47.7%). Two of the four classes were taught by the researcher, while the other two were taught by a different science teacher at the same school. One experimental and one control group were assigned to each teacher. Table 2 provides the student distribution in each group and teacher.

Table 2
Distribution of Sixth Grade Students in the Sample

Groups	Teachers	Female		Male		Total	
		N	**(%)**	***N***	**(%)**	***N***	**(%)**
Experimental-1	Teacher-1	17	15.6	13	11.9	30	27.5
Control-1		12	11	14	12.8	26	23.8
Experimental-2	Teacher-2	16	14.7	11	10.2	27	24.9
Control-2		14	12.8	12	11	26	23.8
Total		59	54.13	50	45.87	109	100

Variables

The dependent variables in this study were the post-test scores of students in the experimental and control groups, measured after the implementation of the lesson plans. These post-test scores were labeled as post-BAS, post-SAS, and post-ADLT. The independent variable was the teaching method applied to each group. This variable was designated as "group" in the statistical analyses. The experimental group received engineering design-based lessons enriched with biomimicry applications, while the control group followed the standard curriculum.

To account for potential differences in baseline knowledge, the pre-test scores of pre-BAS, pre-SAS, and pre-ADLT were used as covariates. By controlling for these pre-test scores, the analysis could isolate the impact of the teaching methods on the dependent variables. This allowed for a more accurate assessment of whether the independent variable (teaching method) had a significant effect on the post-test scores.

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Instruments

In this study, the biomimicry awareness questionnaire (BAQ), the association with daily life test (ADLT), the biomimicry attitude scale (BAS), and the STEM attitude scale (SAS) were used as data collection instruments. Prior to data collection, all four data collection tools were reviewed by two experts in the field of science education. These expert reviews were used for the content validation. Construct validity was assessed using the item-total score correlation, calculated with Pearson's correlation coefficient (r). Items in the instruments were found to have moderate to high positive correlations with the total scores. The internal consistency of data collection instruments was reported as high, with Cronbach's α reliability coefficients ranging from .610 to .902. In this section, these data collection instruments are explained in detail.

The Biomimicry Awareness Questionnaire (BAQ)

The BAQ was developed by researchers to assess sixth grade students' prior knowledge of biomimicry. After expert review and revisions, the final version of BAQ consisted of 20 items. In the questionnaire, students are asked to identify, from four given options, the living organism that inspired the given biomimetic product design. Students were awarded one point for each correct answer and zero for incorrect answers in the questionnaire. The Cronbach alpha reliability coefficient for the BAQ was calculated as .610. The BAQ, which was applied as a pre-test, was used to determine whether there was a significant difference between the awareness of the students in four classes about biomimicry before the implementation. The BAQ pre-test data we obtained were analyzed using One-Way ANOVA in the IBM SPSS 23 program to see whether there was a significant difference among the classes. The analysis revealed no statistically significant differences in the BAQ pre-test scores among the four participating classes ($F(3, 105) = 0.477$, $p = .699$). Thus, the classes were randomly assigned to the experimental and control groups.

The Association with Daily Life Test (ADLT)

After analyzing the daily life association tests prepared in different subjects (Şahin & Bodur, 2016; Yolagiden, 2021), the ADLT was developed by the researchers to measure sixth-grade students' associations with daily life related to the 'sound and its properties' unit. The test consisted of 25 questions aligned with the curriculum objectives in the subject areas of "sound propagation" (4 items), "hearing of sound in different mediums (6 items), "speed of sound" (4 items), and "interaction of sound with matter" (11 items). Expert reviews and revisions were conducted to ensure the quality of the items. The items in the ADLT were designed as 'true', false', and 'don't know'. Correct answers were coded as 1, incorrect answers were coded as 0, and "don't know" was left blank. The Cronbach alpha reliability coefficient for the ADLT was calculated as .776.

The Biomimicry Attitude Scale (BAS)

In order to measure students' attitudes towards biomimicry in the study, the biomimicry attitude scale (BAS) was developed by the researchers. After the literature review, an item pool consisting of statements that measure biomimicry attitudes was developed. The BAS was de-signed in a 5-point Likert type as 'strongly agree', 'agree', 'undecided', 'disagree', 'strongly disagree'. The 24-item scale was developed by taking the expert opinions of a professor in science education and an experienced science teacher. The Cronbach alpha reliability coefficient was calculated as .845 for the BAS.

The STEM Attitude Scale (SAS)

The SAS, used to measure students' attitudes towards STEM, originally developed by Faber et al. (2013) and translated into Turkish by Yıldırım and Selvi (2015), was used in this study. It has four sub-scales: Science, Mathematics, Engineering and Technology, and 21st Century Skills. The scale consists of 37 items in a 5-point Likert-type scale, arranged as 'strongly agree', 'agree', 'undecided', 'disagree', and 'strongly disagree'. The internal reliability of the whole scale, as calculated by Cronbach's alpha, was found to be .902.

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Instructional Materials and Procedure

Lesson Plans for Experimental and Control Groups

Lesson plans are crucial for guiding teachers and ensuring consistent implementation across experimental and control groups to ensure treatment fidelity. In the development of lesson plans, Roobeek's (2019) process was followed. In this study, while preparing the lesson plans, the objectives of the 'sound and its properties' unit were taken into consideration. A literature review was conducted to examine lesson plans previously prepared based on the biomimicry approach and engineering design. As a result of the literature review, biomimicry-enriched engineering design-based lesson plans were created for the experimental group. While preparing the lesson plans of the experimental group, special attention was paid to the contexts and activities that include biomimicry applications, and engineering design-based projects were also integrated into the lesson plans. The lessons for both groups were blended with hands-on activities and experiments in the textbooks within the curriculum. As a result, four biomimicry-enriched engineering design-based lesson plans and four standard curriculum-based lesson plans were prepared for the experimental and control groups, respectively. Table 3 details the implementation activities, objectives, and allocated hours for the lesson plans in both groups.

Table 3
Sixth Grade Sound and Properties Unit Objectives, Lesson Hours and Experimental/Control Group Implementations

Science Topic	Objectives	Lesson Hours	Experimental Group Implementations	Control Group Implementations
Sound Propagation	• Predicts the environments in which sound can propagate and tests their predictions.	4	• Oilbirds and Effects of Noise Pollution on Communication	Textbook EBA Q & A DI
Hearing Sound in Different Medium	• Discovers by experimenting that sounds are heard differently when the sound source changes. • By conducting experiments, students discover how sound changes depending on the medium through which it travels.	6	• Ant Galleria and Musical Instruments	Textbook EBA Q & A DI
Speed of Sound	• Compares the speed of sound in different environments.	4	• Owls and Fast Trains	Textbook EBA Q & A DI
Interaction of Sound with Matter	• Gives examples of reflection and absorption of sound. • Predicts and tests predictions to prevent the spread of sound. • Explains the importance of sound insulation. • Gives examples of acoustic applications. • Designs environments that serve as an example for sound insulation or acoustic applications.	8	• Echolocation of Bats and the Visually Impaired • Mimar Sinan and his work Süleymaniye Mosque	Textbook EBA Q & A DI

[1] EBA: Educational Technology Platform, Q&A: Question and Answer, DI: Direct Instruction.

In experimental groups, students were allowed to explore science topics within the sound and its properties unit in the context of a specific biomimetic scenario. They were then tasked with designing or creating a model inspired by nature. In two of the design activities, namely "Towards the Summit" and "Pantograph Making", students were only required to plan the design or model. However, in the other two design activities, they were expected to create a design or model.

Implementation Procedure/Treatments

The implementation of lesson plans prepared based on a biomimicry-enriched engineering design approach, along with lesson plans prepared based on textbooks as prescribed by the standard curriculum, began in March

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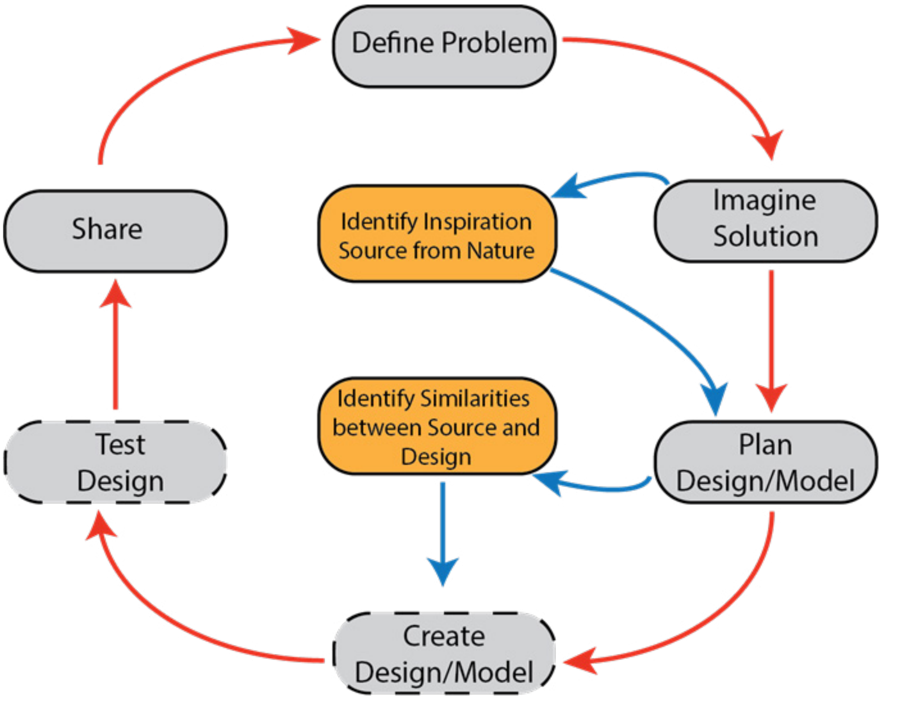
2023 and continued for four weeks, totaling 22 class hours, during the second semester of the academic year. The lesson plans prepared for the experimental and control groups were implemented by two different teachers, one of whom was the researcher. The other teacher was also an experienced teacher in design-based teaching and biomimicry. Before the implementations, the two teachers discussed the lesson plans and implementation procedures to ensure consistent instructions during the procedure.

While implementing lesson plans with a biomimicry-enriched engineering design-based approach in the experimental group, students were divided into cooperative groups of 4-5. These groups were given engineering design activity sheets based on biomimicry principles. Engineering design activities enriched with biomimetic applications were redesigned by incorporating biomimicry practices into the engineering design process cycles found in the literature, as illustrated in Figure 1. This process was implemented in experimental group activities. The aim was to place nature-inspired resources at the center of the engineering design process and to reflect the characteristics of these inspirational sources in the designs. During the lesson, experimental group students were asked to identify the problem situation presented in the activity and find a solution by taking inspiration from nature. The activities included design tasks involving steps such as "defining the problem", "imagining a solution", "identifying an inspiration source from nature", "planning", "identifying similarities between the inspiration source and design", "creating a model by applying the solution", "testing", and "sharing". The red arrows in the figure highlight the core engineering design steps, while the blue arrows indicate the biomimicry enrichment steps integrated into this process. Some of the dashed steps might have been omitted in specific design activities during implementation.

The real-life problems in the activity sheets were read aloud in class, and students were given free time to discuss them within their groups and propose solutions from nature. The classroom teacher guided students as they presented their solution proposals for these problems. Students were given time until the next class to think more about the solutions to the questions at hand, conduct research, review their designs, and gather materials. In the following class, students were given time to present their group's solution proposals and create models based on their designs.

In the control group, the students also worked in cooperative groups of 4-5, using lesson plans that were prepared in accordance with the existing science curriculum. These lesson plans were primarily delivered through presentations, hands-on experiments, questioning with direct instruction, and made use of activities found in the EBA (Educational Technology Platform) and the science textbook.

Figure 1
Biomimicry-Enriched Engineering Design Process



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Data Analysis

For the quantitative analysis to answer the research question, IBM Statistical Package for the Social Sciences (SPSS) 23 was used. For descriptive analysis, we calculated the mean, median, mode, standard deviation, skewness, and kurtosis for each variable in both groups. For inferential analysis, we conducted a Multivariate Analysis of Covariance (MANCOVA) on pre-test and post-test scores. This was done to see how biomimicry enriched engineering design teaching (the independent variable) affected students' attitudes towards biomimicry, association with daily life, and attitudes towards STEM (the dependent variables), while controlling for their pre-test scores.

Ethical Considerations

This study followed the ethical guidelines of the Declaration of Helsinki. Participants gave informed consent after learning about the study's purpose, procedures, their right to withdraw, and data confidentiality. Their data was anonymized using unique, randomly generated IDs to protect privacy and minimize risks. The Institutional Review Board of Kocaeli University approved the study (Approval No: E-10017888-100-366857 and date of approval: 09.02.2023).

Research Results

Descriptive Results

In this study, descriptive statistical analyses were conducted to determine whether the pre-test and post-test scores for both the experimental and control groups followed a normal distribution. These scores were collected before and after the implementations, respectively. Table 4 presents the mean, mode, median, standard deviation, skewness, and kurtosis values of the pre-test and post-test scores obtained from BAQ, ADLT, BAS, and SAS. The skewness and kurtosis values for pre- and post-test scores on the BAQ, ADLT, BAS, and SAS scales for students in the sample were found to be between -1 and +1. Therefore, as the skewness and kurtosis values did not exceed the critical range and the mean, median, and mode were approximately equal, the scores were assumed to be normally distributed (Pallant, 2016).

Table 4
Descriptive Statistical Findings Related to Pre-Test BAQ and Pre- and Post-Tests of ADLT, BAS, and SAS

	Instrument	Group	*M*	*Mdn*	*Mo*	*SD*	Skewness	Kurtosis
PRE-TEST	BAQ	E1	5.97	6	8	1.750	0.756	1.001
		C1	5.81	6	8	2.191	-0.179	-0.509
		C2	5.65	5	9	1.999	-0.780	1.008
		E2	5.44	6	9	1.739	-0.278	-0.943
		Total	5.72	6	10	1.905	0.248	0.148
PRE-TESTS	ADLT	E	11.79	12	12	3.069	-0.048	-0.476
		C	11.37	11	8	3.608	0.228	-0.944
		Total	11.67	10	12	3.360	0.021	-0.599
	BAS	E	77.46	77	70	14.68	0.032	-0.077
		C	80.21	79.5	73	14.335	0.103	-0.674
		Total	78.78	78	73	14.50	0.054	-0.365
	SAS	E	120	120	119	22.02	-0.950	-0.24
		C	124.23	124	112	24.80	-0.334	0.136
		Total	122.14	122	112	23.37	-0.192	0.090

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	Instrument	Group	*M*	*Mdn*	*Mo*	*SD*	Skewness	Kurtosis
POST- TESTS	ADLT	E	18.4	19	22	3.80	-0.514	-0.146
		C	11.94	12	12	3.90	-0.146	-0.874
		Total	15.33	16	20	5.07	-0.166	-0.782
	BAS	E	85.6	86	86	11.85	0.090	-1.001
		C	77.98	75.5	68	15.86	-0.053	-0.636
		Total	82	80	86	14.37	-0.225	-0.415
	SAS	E	133.98	136	143	20.74	-0.233	-0.383
		C	121.32	123.5	118	26.30	-0.710	0.867
		Total	127.94	130	118	24.29	-0.666	0.924

E: Experimental, C: Control, M: Sample mean, Mdn: Median, Mo: Mode, SD: Standard Deviation

Inferential Results

Preliminary Assumption Checks and Determining Covariates

For MANCOVA analysis to be conducted, a series of assumptions must be met. These assumptions were tested, and the results were evaluated for: sample size, normality, Levene's test for equality of variances, univariate and multivariate outliers, multicollinearity and singularity, homogeneity of variance-covariance matrices, and homogeneity of regression. Based on the results, as the assumptions were met, there were no issues with proceeding with the MANCOVA analysis.

In this study, the pre-test scores of ADLT, BAS, and SAS were considered as potential covariates to reduce error variance and eliminate systematic bias. According to Stevens (2009), even if groups do not differ significantly in terms of pre-test scores, pre-test scores should still be used as covariates to reduce error variance. In this study, no statistically significant difference was found between the pre-test scores of BAS (t(107) = 0.99, p = .325), SAS (t(107) = .88, p = .383), and ADLT (t(107) = .66, p = .509) for experimental and control group students. For these reasons, these three pre-test scores were selected as covariates. According to Pallant (2016) and Stevens (2009), covariates should be continuous variables, the reliability of scores obtained from the covariate should be high (>0.70), and covariates should have a significant correlation with the dependent variables, while the correlation between covariates should be less than .80. When Table 5 is examined, the biomimicry awareness questionnaire (pre-BAQ) used to equalize the groups was not selected as a covariate because both its reliability was below .70 (α = .610) and it did not have a significant correlation with the dependent variables post-BAS, post-ADLT, and post-SAS. On the other hand, pre-BAS, pre-ADLT, and pre-SAS were determined as covariates because they had significant correlations with the dependent variables and had correlations less than .80 with each other.

Table 5
Correlations between Covariates and Dependent Variables

Variables	pre-ADLT	pre-SAS	pre-BAS	post-ADLT	post-SAS	post-BAS
pre-BAQ	.160	.151	.017	.175	.171	.056
pre-ADLT		.267**	.007	.497**	.246*	.039
pre-SAS			.562**	.156	.572**	.335**
pre-BAS				.105	.518**	.684**
post-ADLT					.475**	.382**
post-SAS						.685**
post-BAS						1

**Correlation is significant at the .01 level (2-tailed).
* Correlation is significant at the .05 level (2-tailed).

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MANCOVA Results

In this study, a MANCOVA analysis was conducted to determine if there was a significant difference between the experimental and control groups in their post-test total scores for BAS, SAS, and ADLT. The analysis controlled the effects of pre-test scores for these same variables. Teaching methods (experimental and control group implementations) named as group served as the independent variable, while the post-test scores for BAS, SAS, and ADLT were the dependent variables. The pre-test scores for these variables were used as covariates. The results of the MANCOVA analysis are presented in Table 6.

Table 6
MANCOVA Results

Independent Variables	Wilks' Λ	*F*	*df1*	*df2*	*p*	η^2	Observed Power
Intercept	0.845	6.25	3	102	0.001	0.155	0.845
pre-ADLT	0.648	18.44	3	102	< .001	0.352	0.648
pre-SAS	0.762	10.64	3	102	< .001	0.238	0.762
pre-BAS	0.520	31.33	3	102	< .001	0.480	0.520
Group (experimental-control)	0.460	39.88	3	102	< .001	0.540	0.460

According to MANCOVA analysis, results indicated a statistically significant difference between the experimental and control groups in terms of post-test scores for BAS, SAS, and ADLT, after controlling for the pre-test scores ($F(3, 102) = 39.88$; $p < .001$; Wilks' $\Lambda = 0.460$; partial eta squared = 0.540). To determine which specific dependent variables contributed to this significant difference, a post hoc analysis was conducted. Using a Bonferroni correction, a significance level of .017 was determined. The results showed that the post-test scores for ADLT ($F(1, 104) = 113.43$, $p < .001$, partial eta squared = 0.522), BAS ($F(1,104) = 27.04$, $p < .001$, partial eta squared=0.206), and SAS ($F(1,104) = 20.68$, $p < .001$, partial eta squared = 0.166) were all significantly different between the experimental and control groups at the .017 level. These results indicate that, after controlling pre-test scores, there was a significant difference between the experimental and control groups in terms of post-test scores for biomimicry attitudes, daily life associations, and STEM attitudes. To determine the magnitude of these differences, effect sizes (eta squared, η^2) were calculated. Eta squared indicates the proportion of variance in the dependent variable that is accounted for by the independent variable. The results showed large effect sizes for all three dependent variables (ADLT $\eta^2 = 0.522$; SAS $\eta^2 = 0.166$; BAS $\eta^2 = 0.206$), with the largest effect size for ADLT post-test scores (Table 7).

Table 7
Comparison Results of Groups for Dependent Variables

	Dependent Variables	*df*	*MS*	*F*	*p*	η^2
Group	post-ADLT	1	1073.102	113.43	p < .001	0.522
	post-SAS	1	6305.656	20.68	p < .001	0.166
	post-BAS	1	2417.463	27.04	p < .001	0.206

When examining the comparison results obtained by looking at the values from the MANCOVA, it was observed that there was a significant difference in favor of the experimental group in terms of post-test scores for ADLT, BAS, and SAS ($p < .05$). According to the results, it is observed that the mean post-test score for ADLT in the experimental group ($M = 18.353$, $SD = 0.409$) is higher than the mean score of the control group ($M = 12.017$, $SD = 0.428$), indicating a difference in favor of the experimental group. Similarly, the mean post-test score for SAS in the experimental group ($M = 135.272$, $SD = 2.322$) is higher than the mean score of the control group ($M = 119.914$, $SD = 2.432$), indicating a difference in favor of the experimental group. Likewise, when looking at the mean post-test scores for BAS, the mean of the experimental group ($M = 86.537$, $SD = 1.258$) is greater than the mean of the control group ($M = 77.027$, $SD = 1.317$), indicating a difference in favor of the experimental group. To sum up, the experimental

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groups performed better than the control groups on all three measures (ADLT, SAS, and BAS). The average scores for the experimental groups were higher than the average scores for the control groups in each case.

Discussion

During the implementation of this study, the biomimicry-enriched engineering design activities conducted in the experimental group fostered an active learning environment. Students collaborated in small groups, with teacher guidance, to solve and explore real-world problems, drawing inspiration from nature for solutions. This active, real-life-connected learning approach, inherent in the biomimicry-enriched engineering design teaching, likely improved the experimental group's ability to relate sound concepts to their everyday experiences compared to the control group. One key finding of the study was that the largest effect was observed in students' ability to associate scientific concepts with daily life (Table 7). This suggests that biomimicry, as a teaching approach, is particularly effective in helping students see the relevance of science beyond the classroom. This result is consistent with Gardner's (2012) assertion that biomimicry encourages students to think creatively about real-world problems by observing and learning from nature. Furthermore, the engineering design activities allowed students to work collaboratively, fostering a deeper understanding of the material and enhancing their problem-solving abilities, as suggested by Hynes et al. (2011). Students generally find sound a challenging science concept (Caleon & Subramaniam, 2010; Eshach & Schwartz, 2006; Küçüközer, 2009; Wittmann et al., 2003) and have trouble relating it to their everyday experiences (Aksoy et al., 2023). In fact, knowledge that cannot be related to daily life cannot go beyond mere memorization (Demircioğlu et al., 2012). When the instructional material is relevant to their lives, however, students find the content more useful and learn it more meaningfully. The current study found that biomimicry-enriched engineering design-based teaching was an effective way to help students understand the relevance of science to their daily lives (Pauls, 2017). This approach made the subject more engaging and meaningful, leading to a stronger association with daily life in the sound and its properties unit, as well as increased attitudes toward biomimicry and STEM compared to control group teaching.

By focusing on biomimetic examples, such as the use of echolocation by dolphins or sound insulation inspired by owl feathers, students in the experimental group were able to see how the principles of sound propagation, reflection, and insulation are used both in nature and in human-made technologies. This association with daily life is critical because it enhances students' engagement, motivation, and retention of knowledge (Ersanlı, 2016; Jacobs et al., 2022; Kandemir et al., 2022; Kara, 2016; Savran Gencer et al., 2020; Sumrall et al., 2018) and their success in science. By involving students in such activities, the instructional approach fostered situated learning, where students' understanding of abstract scientific concepts is grounded in practical, real-life problems (Lave & Wenger, 1991; Rehmat et al., 2024). This is particularly important for topics like sound, where students often struggle to visualize how sound waves behave in different environments. The hands-on nature of the biomimicry-enriched tasks, such as designing soundproofing solutions or examining the different mediums through which sound can travel, helped students conceptualize how these principles apply in everyday scenarios, such as controlling noise pollution or improving communication systems (Gardner, 2012). Furthermore, the biomimicry approach likely promoted deeper cognitive processing, as students were not only required to understand the concept of sound but also to analyze, synthesize, and evaluate how nature solves sound-related challenges. For instance, students' designs that mimicked owls' silent flight for sound insulation or dolphins' echolocation for communication systems demonstrated their ability to transfer their understanding of sound from biological examples to human-designed technologies. This ability to transfer knowledge across domains is a key indicator of meaningful learning and the development of critical thinking skills (Faber et al., 2013; Fortus et al., 2005).

The findings of this study revealed that biomimicry-enriched engineering design-based teaching significantly improved students' attitudes toward STEM. This positive shift in STEM attitudes aligns with previous research emphasizing the role of innovative teaching strategies, such as engineering design-based learning, in promoting student interest and engagement in STEM disciplines (NAENRC, 2014; Ring et al., 2017). Biomimicry is very suitable for gaining engineering design skills as a solution-oriented approach with thinking skills. From this, it can be inferred that one of the effective methods that will contribute to students' invention and creativity development with inspiration from nature is the STEM approach (Gardner, 2012; Sumrall et al., 2018). For this reason, biomimicry research, which includes STEM or engineering design-based education in schools, contributes to the development of individuals' abilities in various fields by comparing them with experiential learning environments and real-life problems (Avcı, 2019). In particular, the integration of biomimicry in the instructional process appears to provide students with a hands-on, interdisciplinary approach to learning that fosters positive attitudes toward STEM fields. This is consistent

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with findings from studies such as Gencer et al. (Savran Gencer et al., 2020), which highlight that students exposed to design-based learning are more likely to develop favorable attitudes toward science and engineering.

The results of the study suggest that biomimicry, as a pedagogical tool, not only enhances students' cognitive understanding of STEM topics in relation to real life contexts but also positively influences their affective dispositions toward learning science. The improvement in biomimicry attitudes is consistent with prior research, such as that of Gardner (2012), who argues that nature-inspired learning encourages curiosity and engagement by showing students the relevance of science in solving real-world problems. By integrating biomimicry into the engineering design process, students are exposed to the practical applications of scientific knowledge, fostering a sense of wonder and appreciation for how nature can inspire technological solutions (Pauls, 2017), which in turn develops a positive attitude towards biomimicry. Moreover, the strong positive shift in biomimicry attitudes in this study can be attributed to the hands-on, nature-inspired design tasks that students engaged in during the lessons. For example, activities such as creating sound-insulating designs inspired by owl feathers or using ant galleries in whistling acacia as a model for building musical instruments provided students with tangible, relatable examples of how biomimicry works. These activities helped students connect abstract scientific concepts to concrete, real-world applications, which is crucial for developing positive attitudes toward learning (Canbazoğlu Bilici et al., 2021; Kaltakci & Eryilmaz, 2011). As suggested by research in affective education, students who find personal relevance and emotional engagement in their learning tasks are more likely to develop positive attitudes toward the subject matter (Faber et al., 2013).

Although the study's results are promising, it is important to recognize its limitations. One potential challenge is the need for adequate teacher training and resources to implement biomimicry-enriched engineering design lessons effectively. Not all teachers may feel comfortable integrating biomimicry into their lessons without appropriate professional development and support (NAENRC, 2014). As such, future research could explore the most effective ways to train teachers in this approach and provide them with the necessary tools and resources. Additionally, while this study focused on sixth-grade students, future research could investigate how biomimicry-enriched teaching influences STEM attitudes, association with daily life, and biomimicry attitude across different grade levels. The study focused on a specific set of sound-related concepts, and the effectiveness of the teaching design may vary across other scientific topics. Future research should explore whether similar improvements in the association with daily life can be achieved in other science units, such as electricity or motion. Additionally, further research is needed to explore how these factors develop over time. Longitudinal studies could investigate whether the positive effects observed in this study persist as students advance through higher levels of education and whether they continue to apply biomimicry concepts in other areas of science and technology. It would also be valuable to examine the effects of biomimicry-enriched teaching on students from diverse educational backgrounds to determine whether these findings are generalizable across different populations. Finally, future studies could incorporate more detailed qualitative methods, such as interviews or classroom observations, to gain a deeper understanding of how students make connections between science concepts and daily life during biomimicry-enriched teaching.

Conclusions and Implications

This study examined the effects of biomimicry-enriched engineering design-based activities on 6th-grade students in the "Sound and its Properties" unit. The findings of the study indicate that biomimicry-enriched engineering design-based teaching significantly enhances students' association with daily life, attitudes toward biomimicry, and STEM. Globally, there's a demand for innovative methods to make science education more relevant to real-life situations. One promising approach is biomimicry, which allows students to observe science in action and connect theoretical concepts with practical applications in nature. By exposing students to nature-inspired solutions and allowing them to engage in hands-on design activities, this instructional approach not only fosters creativity and innovation but also instills a deeper appreciation for the relevance of science in everyday life. These results suggest that biomimicry in engineering design-based applications can play a vital role in improving STEM education by making scientific concepts more engaging, relatable, and applicable to real-world challenges. This study not only addresses specific educational needs but also contributes to the international discourse on effective STEM education. The principles and outcomes observed in this biomimicry-enriched approach have broad applicability across diverse global contexts, offering insights for enhancing student engagement and attitudes in science education worldwide.

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This study has several educational implications derived from the results regarding students' association with sound concepts in daily life, their STEM attitudes, and their biomimicry attitudes. To begin with, the improvement in students' association with sound concepts in daily life highlights the importance of integrating real-world contexts into science education. Teachers should incorporate biomimetic examples, such as animal echolocation or noise control inspired by nature, to make abstract concepts more accessible and engaging. By connecting the properties of sound, such as reflection and insulation, to familiar contexts—whether natural or technological—students can develop a more nuanced understanding of the subject matter, which in turn can lead to greater engagement and improved learning outcomes. Moreover, this approach encourages students to think about science in a more integrated, interdisciplinary way. The association of sound concepts with daily life is not limited to physics; it also involves engineering (soundproofing designs), biology (echolocation in animals), and even environmental science (noise pollution). This interdisciplinary thinking is a key goal of STEM education, which seeks to prepare students to solve complex, real-world problems that do not fall neatly into one subject area. Secondly, the positive shift in STEM attitudes suggests that interdisciplinary approaches can significantly enhance student engagement. Combining biology, physics, and engineering in biomimetic tasks prepares students for complex problem-solving, a key skill for future STEM careers. Moreover, the interdisciplinary and creative aspects of the biomimicry-enriched design tasks likely contributed to the enhanced STEM attitudes observed in this study. Unlike conventional classroom activities, design-based tasks allowed students to take ownership of their learning by developing solutions to real-world problems, promoting a sense of agency and accomplishment. Thirdly, the enhancement of biomimicry attitudes underscores the potential of nature-inspired design to foster creativity. By drawing on natural examples, teachers can provide students with a more relatable and engaging way to understand complex scientific concepts, potentially making STEM subjects more accessible and appealing to a broader range of students. Additionally, the improvement in biomimicry attitudes could have long-term implications for students' career interests and aspirations in STEM fields. Positive attitudes toward biomimicry may inspire students to pursue further studies or careers in fields such as environmental engineering, biology, and sustainable technology, where biomimicry plays a crucial role. As the global emphasis on sustainability and innovation grows, developing a generation of students who are not only proficient in STEM but also passionate about nature-inspired solutions could be vital for future technological advancements. Finally, the success of this intervention suggests a need for curricula that emphasize hands-on, design-based learning. Policymakers and educators should consider integrating biomimicry into STEM education to better prepare students for sustainable innovation.

Declaration of Interest

The authors declare no competing interest.

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THE EFFECTS OF INTEGRATING STEM DESIGN THINKING INTO EDUCATION FOR SUSTAINABLE DEVELOPMENT ON STUDENTS' SCIENTIFIC MODELING SKILLS

Heru Edi Kurniawan, Sulistyo Saputro, Suranto, Murni Ramli

Abstract. *Scientific modeling is a fundamental tool in STEM education that facilitates the understanding and explanation of complex phenomena. This study examines the effects of the STEM Modelling Design Thinking (STEM MDT) compared to the STEM Project Based Learning (STEM PjBL), particularly in the context of Education for Sustainable Development (ESD), in enhancing students' scientific modeling skills. Using a quasi-experimental design with non-equivalent pre-test and post-test control groups, the study involved 108 ninth-grade students in the experimental group (55 students) who participated in the STEM MDT, while the control group (53 students) engaged in STEM PjBL. Data were collected by evaluating scientific modeling skills before and after the intervention. The results indicated that the STEM MDT significantly improved students' scientific modeling skills, with effect sizes ranging from moderate to very large (Cohen's d = .91), compared to moderate improvement (Cohen's d = .43). These findings suggest that integrating ESD within the STEM MDT framework not only enhances scientific modeling competencies but also equips students to address complex real-world challenges. This study highlights the potential of STEM MDT as an innovative pedagogical approach for educators and policymakers seeking to cultivate essential skills in future generations.*

Keywords: *scientific modeling, STEM education, design thinking, education for sustainable development, project based learning*

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Introduction

To address the demands of 21st-century education, adopting creative instructional strategies that are seamlessly incorporated into the teaching process is crucial for developing learners with global competencies, particularly through the application of the Science, Technology, Engineering, and Mathematics (STEM) framework. The STEM approach integrates multiple disciplines to strengthen students' grasp and mastery of key foundational knowledge, as well as cultivating skills necessary for the 21st century (Akcan et al., 2023; Wan et al., 2021). The skill of interpreting concepts in science education through STEM is supported by skills in scientific modeling, where the development of scientific models represents something that may be too small to see or too large to imagine, for example, the Bohr model of the atom (Schwarz et al., 2009). One of the primary tools in STEM education is scientific modeling, which helps students understand and explain complex phenomena (Bielik et al., 2018; Schwarz et al., 2009b; Van Driel & Verloop, 2002). The significance of this research lies in its contribution to addressing global challenges through science education by linking students' modeling competencies with real-world problems, particularly those related to climate change. Although much attention has been paid to SDG 4 (Quality Education), this study extends its relevance to SDG 13 (Climate Action) by integrating Education for Sustainable Development (ESD) into STEM learning. The STEM approach facilitates interdisciplinary learning that empowers students not only to understand abstract scientific concepts through modeling but also to apply that understanding in meaningful ways, such as designing context-based projects that offer solutions to environmental problems around them (Sutaphan & Yuenyong, 2023). This approach makes science education more relevant, action-oriented, and impactful across different generations. In this way, scientific modeling serves not only as a cognitive bridge to support conceptual understanding but also as a core competency to enable students to become problem solvers and active agents of change in their local and global communities (Krell & Krüger, 2016). Through modelling, students learn to identify relevant variables, understand the relationships between the components within a system, and make predictions based on the models they create (Krell et al., 2019; Krell & Krüger, 2016). This method corresponds

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to the primary goals of STEM education, which emphasize the development of competencies such as working collaboratively, communicating clearly, and addressing problems effectively (Baran et al., 2021).

A scientific model is a simplified and abstract representation of a system or set of phenomena that effectively illustrates its main attributes, and can be utilized to create explanations and forecasts (Harrison & Treagust, 2000). The development and utilization of scientific models are key practices in the fields of science and engineering (Bamberger & Davis, 2013). Models are utilized as tools to clarify and anticipate phenomena, represent the interactions among components in a system, and support problem solving and the exchange of ideas (Schwarz et al., 2009). Schneider (1984) and Vieira Kritz (2023) highlight three fundamental features that characterize models: (i) they are representations or mappings of their original objects; (ii) they always simplify the original object by representing only selected attributes; and (iii) the choice of these attributes is pragmatic and influenced by the model user, the timing of use, and the specific purpose of the model. The development and application of scientific models are critical practices in science and engineering, where they explain the interactions between system components. Developing and using scientific models is a crucial practice in science and engineering, where models serve to explain the interactions between components within a system (Donovan & Bransford, 2005). Although students may use models in ways that diverge from scientific usage, it is vital to immerse them in modeling practices that mirror the work of scientists, encompassing the processes of constructing, employing, assessing, and revising models.

However, scientific modelling is rarely integrated into the educational experiences of students at the elementary and secondary levels (Schwarz et al., 2009). There are often insufficient opportunities for students to engage with models, and many teachers do not have access to high-quality curricular materials that encourage the use of scientific modeling (Chiu & Lin, 2018; Chiu & Lin, 2019). Within this framework, the design-thinking approach has been shown to be an effective teaching method for enhancing students' creative self-efficacy and promoting their interest in modeling skills (He et al., 2023; Tsai et al., 2021). The design thinking process is an iterative approach that involves understanding users, identifying problems, designing optimal solutions, and conducting experiments. When applied in a STEM context grounded in ESD, this process can effectively enhance students' competencies by fostering critical thinking, creativity, collaboration, and real-world problem solving aligned with sustainability goals (Fan & Yu, 2017).

ESD empowers learners with the necessary knowledge, skills, and values to effectively navigate and respond to a fast-changing world, encouraging active participation in achieving Sustainable Development Goals (SDGs) (Setyowati et al., 2022). The core of ESD is fostering systemic thinking and analysis by engaging with real-world case studies, critical incidents, and project-based learning experiences. Current international discourse highlights eight core sustainability competencies essential for fostering transformative change (Brundiers et al. 2021, 2021). These include systems thinking competence, which involves understanding the relationships within complex systems and managing uncertainty; anticipatory competence, which focuses on evaluating future scenarios and potential consequences; and normative competence, which emphasizes reflecting on values and negotiating sustainability goals amid conflicting interests. Additionally, strategic competence is related to designing and implementing innovative sustainability actions, while collaborative competence involves empathizing and engaging in participatory problem solving. Critical thinking competence encourages questioning assumptions and reflecting on values, whereas self-awareness competence is about understanding one's role and responsibilities within the community. Finally, integrated problem-solving competence applies interdisciplinary approaches to develop inclusive and sustainable solutions (Rieckmann, 2022). Together, these competencies empower learners to become effective agents of transformative change.

Although many previous studies indicate that ESD and STEM-based methodologies can contribute to the development of 21st-century skills, most have not examined the specific function of STEM in modeling education within the context of ESD, utilizing design thinking (Hanif et al., 2019; He et al., 2023; Lin & Tsai, 2021; Lin et al., 2021). In fact, integrating STEM design thinking has the potential to add rich and relevant contextual dimensions to students, increasing their engagement in learning and training them in scientific modelling (Fan & Yu, 2017). Furthermore, the exploration of design thinking models has been conducted in the context of STEM education in secondary schools to increase student interest (Wingard et al., 2022).

Within a modeling-based viewpoint, the focus is on the construction and refinement of scientific models, as well as the interplay between teaching and learning processes, and the formation of mental models (Papaevripidou et al., 2014). The use of modeling can create a setting in which the construction and refinement of models yield higher-quality results than those currently attainable through other educational environments or resources (Louca et al., 2011). Through participation in these contexts, students can construct understanding models that support their internalization and lead to a more in-depth understanding of the phenomena being explored (Schwarz et

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al., 2009; Schwarz & White, 2005). Furthermore, the application of the STEM approach in educational settings is frequently general and does not prioritize direct relevance to real-life scenarios, which is vital for preparing students to address global issues and solutions in social, economic, and environmental contexts (Asrizal et al., 2022; Ladachart et al., 2022). Thus, more specific research is required to analyze the effects of educational models that merge the STEM design thinking approach with ESD issues in enhancing students' abilities in scientific modeling.

Literature Review

Integrating STEM design thinking into ESD has shown considerable promise in strengthening students' scientific modeling skills at all educational levels. Yalçın (2024) stated that design-based STEM activities can substantially and durably improve 21st century competencies, such as life and career skills, innovation and learning abilities, and digital literacy, even in preschool-aged children. This suggests the significant early developmental potential of such interventions in enhancing scientific modeling skills. This aligns with the findings of Papadakis and colleagues, who demonstrated that developmentally appropriate mobile applications, programming platforms like App Inventor, and robotic kits such as Lego Mindstorms NXT can effectively foster computational thinking and STEM-related skills in early childhood and teacher education contexts (Kalogiannakis & Papadakis, 2020; Papadakis, 2019; Papadakis & Orfanakis, 2017).

Furthermore, the use of design-based pedagogy and tools, such as 3D printing, in integrated STEM programs has been linked to a better understanding of the design process and mindset needed for effective scientific modeling (Zhou et al., 2020). Systems thinking and conceptual modeling have also been promoted through interdisciplinary approaches, which significantly benefit both engineering students and educators (Peretz et al., 2023). Experiential learning methods, such as field trips and collaborative learning, have proven effective in developing students' systems thinking abilities by immersing them in complex real world contexts (Demssie et al., 2023).

Studies increasingly emphasize that incorporating models into science curricula is indispensable for nurturing students' scientific literacy and problem-solving competencies. Innovations in technology now allow easier model manipulation and refinement, supporting a more hands-on and evolving approach to science education and research. The application of models in educational contexts, as demonstrated by numerous studies, emphasizes their importance in promoting a more profound comprehension of intricate phenomena. For instance, Peretz et al. (2023) underscored the importance of applying mathematical modeling to real-world scenarios, demonstrating how such models can connect theoretical mathematical concepts with their real-life applications. Böschl et al. (2023) highlighted the importance of incorporating authentic scientific modeling practices in elementary classrooms, noting that while students often engage in model construction, there is a lack of opportunities for model evaluation and revision, which are crucial for a comprehensive understanding of scientific phenomena. The use of machine learning to assess student-developed models, as explored by Zhai et al. (2022), demonstrates the potential of technology to provide timely feedback, thus supporting teachers in integrating modeling tasks into their instruction. Bowers et al. (2023) further explored the role of computational system modeling in education, emphasizing the importance of testing and debugging as part of the modeling process, which helps students refine their models and deepen their understanding.

Therefore, fostering scientific modeling skills through the integration of STEM-MDT within the context of ESD is crucial to align science education with the epistemic knowledge framework outlined in the Programme for International Student Assessment (PISA) (OECD, 2025). Scientific modeling enables students to construct and evaluate representations of complex phenomena, predict outcomes, and propose core competencies for solutions, as emphasized in the PISA framework (OECD, 2025; L. Zhang et al., 2023). Through modeling, students developed a deeper understanding of the nature and purpose of science, the distinction between models and reality, and the limitations and predictive power of different types of models. This approach not only equips learners to engage with sustainability challenges in meaningful ways but also prepares them to meet international benchmarks of scientific literacy and inquiry based competence as defined by PISA.

Research Aim and Research Question

STEM Modelling Design Thinking (STEM MDT) is a learning model that integrates STEM education with the design thinking approach at the level of real world applications, aiming to improve scientific modelling skills. This study aimed to compare the effects of STEM MDT and project-based learning (STEM PjBL) models in enhancing students' scientific modelling skills within the context of ESD issues. Through a more detailed analysis of the effect

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sizes on each aspect of scientific modelling skills, this research is expected to strengthen empirical evidence on the effects of STEM MDT. The findings of this study are expected to provide significant contributions to pedagogical frameworks and encourage educators and policymakers to consider STEM MDT a breakthrough innovation in science education. The guiding research question for this study was:

What were the effects of the STEM-MDT learning model on scientific modelling skills compared with the STEM-PjBL learning model in the context of ESD issues?

Research Methodology

General Background

This study employs a quasi-experimental methodology that incorporates a pretest-posttest design along with a nonequivalent control group (Reichardt, 2019). The process includes collecting data before and after the intervention in two groups: one group receiving treatment and the other functioning as a control, as shown in Figure 1 (Creswell, 2018). The steps in the research procedure are as follows: first, a pretest measuring scientific modeling capability is given to both the experimental group and the control group; second, implementing the STEM Modelling Design Thinking (STEM MDT) in the experimental group (EG) and the STEM Project-Based Learning (STEM PjBL) in the control group (CG); third, administering a posttest on scientific modeling ability for both groups. The effects of the STEM MDT were evaluated by analyzing and comparing the pretest and posttest scores for each aspect of scientific modelling ability between the two groups. Conducted over four weeks, this study was implemented in science classes at SMP IT Nur Hidayah Surakarta from October to December 2024. The educational content focused on climate change issues in the context of ESD (Shaw et al., 2021).

This study was conducted in accordance with ethical standards involving research with human participants. Prior to the implementation of the research, written informed consent was obtained from all participating students and their guardians. Participation in the study was voluntary, and anonymity and confidentiality of participants' responses were maintained throughout the research process. Ethical approval for the study was granted by the Surakarta City Education Office (Approval Letter Number: PN.01/7532/VIII/2024), which facilitated coordination between the participating schools. The testing procedures were approved by both school principals and science teachers, who directly supervised the implementation. Furthermore, a permission letter (Number: 17651/UN27/PK/PK.03.08/2024) was issued to SMP IT Nur Hidayah, allowing data collection from respondents without coercion. Before data collection, all students were thoroughly informed of the purpose and procedures of the study. The study ensured that participation was fully voluntary, complete confidentiality and anonymity were guaranteed, and informed consent was obtained from all students who participated in the scientific modeling evaluation. This approval confirmed that the study complied with national research ethics policies and adhered to international ethical guidelines, including the principles outlined in the Declaration of Helsinki. Although the study was quasi-experimental and not a clinical trial, the reporting structure was reviewed against relevant items from the CONSORT 2010 checklist to ensure transparency, methodological integrity, and ethical compliance.

To ensure fidelity of implementation, the science teacher in the experimental group participated in a two-day intensive training focused on core components of the STEM Design Thinking framework, such as problem identification, scientific modelling, ideation, prototyping, and iterative refinement (Kelley et al., 2020). The training was guided by structured modules, standardized lesson plans, and sample teaching scripts to ensure consistency across instructional sessions (Chevalier et al., 2020). During this training, the teacher also facilitated group discussions, guided student investigations, and evaluated modelling outcomes based on the developed rubrics.

To minimize potential teacher bias, the teachers assigned to the experimental and control groups were different individuals with similar implementation phases by independent observers using structured fidelity checklists and evaluation rubrics(Huang et al., 2022). Additionally, teacher reflection journals and debriefing interviews were used to support continuous improvement and ensure alignment with the intended instructional model. Both the experimental and control groups were taught by teachers with qualifications and teaching experience comparable to the control for teacher effects (Ragusa, 2011), and weekly coordination meetings helped ensure consistent implementation across classrooms (Latip et al., 2023).Weekly coordination meetings involving the research team and classroom teachers were held to address implementation challenges, reinforce pedagogical fidelity, and clarify instructional procedures (Latip et al., 2023). Furthermore, participant selection was carefully performed to ensure comparability between the experimental and control groups. Students were matched based on grade level, prior academic performance in science, and gender distribution. This matching strategy is essential for controlling

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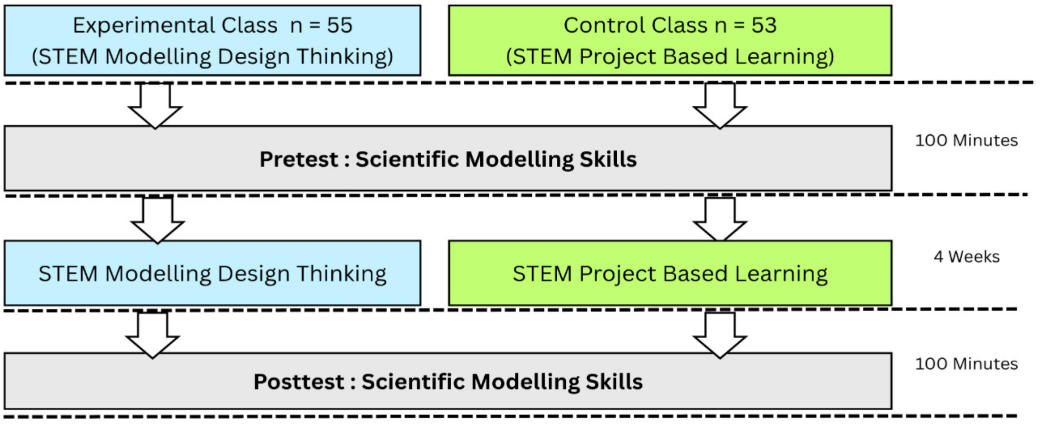
extraneous variables and enhancing internal validity (Balkin & Lenz, 2021; Reichardt, 2019). Collectively, these methodological strategies include comprehensive instructor training, mitigation of teacher bias, fidelity monitoring, consistent instructional tools, and matched group selection aligned with best practices in quasi-experimental research design, and contributed to the robustness of the study's internal validity (Skourdoumbis & Gale, 2013).

Figure 1
Procedure of Experiment



Initially, both classes underwent a pretest to assess their scientific modeling skills, which lasted 100 minutes and was conducted in October 2024. The study, involving both experimental and control classes, was conducted over four weeks from October to December 2024. During this period, the experimental class participated in STEM Modelling Design Thinking (STEM MDT), while the control class engaged in STEM Project Based Learning (STEM PjBL). After the four-week period, both classes took a posttest to evaluate their scientific modeling skills again, which lasted for 100 minutes. This structured approach enabled a comparative analysis of the effects of different STEM educational methodologies implemented from October to December 2024.

Population and Sample

The study population consisted of 181 ninth-grade students at SMP IT Nur Hidayah Surakarta, a private institution located in Central Java, Indonesia. Using purposive sampling, the sample was selected based on relevant criteria that focused on ninth-grade students in science, where the curriculum includes topics related to climate change in accordance with national standards. The criteria align with the purpose of this study, which is to evaluate how the STEM MDT affects the improvement of scientific modeling skills related to climate change. The purposive sampling method was used because researchers could selectively choose samples according to the characteristics of the phenomenon under study, thus obtaining significant information about this study. The chosen sample comprised 55 ninth-grade students in the experimental group and 53 in the control group. The sample size was determined based on the number of participants who met the inclusion criteria. These criteria included willingness to participate, ability to participate in the intervention, and ensuring a balanced group size to facilitate a comparative analysis. The Experimental Group (EG) used the STEM MDT, whereas the Control Group (CG), serving as a comparison of the experimental outcomes, employed STEM PjBL. The selected research participants were both capable and willing to participate in this study while ensuring the confidentiality of their identities. This approach minimizes potential selection bias and improves the internal validity of the study (Changwong et al., 2018).

Procedures

Experimental groups

The experimental group was treated by applying the STEM MDT, which has the advantage of incorporating minds-on and hands-on designs in scientific modeling practices through the phases of science and engineering,

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focusing on climate change issues as the main problem presented in learning. This acts as a stimulus for students to engage in scientific modeling, thereby improving their understanding. Climate change issues in this experimental group were integrated with ESD aspects, which involved environmental, social, and economic dimensions. This integration facilitates the exploration of diverse perspectives through discussion. The process of selecting the experimental class for research is an important step that deserves careful attention. This selection process considered the characteristics of the participants in accordance with the research objectives.

In this experimental group, the STEM MDT learning model represented an integration of the STEM approach and modeling components. The elements of the STEM MDT model consisted of (1) a learning syntax with five phases, (2) social systems, (3) reaction principles, (4) support systems, and (5) instructional impacts. The phases and subphases of the STEM MDT learning model are systematically arranged frameworks that direct students in solving scientific and social problems from the problem orientation stage to the reflection stage. These phases illustrate the essential steps in the learning process designed to achieve the intended outcomes, while the sub-phases provide more granular steps within each phase that support students' participation in a structured learning experience. The phases and subphases of the STEM MDT learning model are listed in Table 1.

Table 1
Phases and Subphases of STEM MDT

Phases	Sub-Phase	Learning Activity
		Phase 1: Scientist
Empathize	Observation	Observing phenomena or situations to gather initial information and explore user needs through direct observation and interaction, based on the ESD context: economy, society, environment.
		Conducting experiments or interventions to understand phenomena based on the ESD context obtained from the empathize phase.
Define	Manipulation	
Modelling	Minds On modelling (initial Model)	Creating representations of proposed solutions, such as diagrams, simulations, models, patterns, or relationships, using tools like SageModeler, Canva, or mind mapping in ESD contexts.
	Verification (model revision)	Re-testing hypotheses or models with additional data or further information based on ESD.
	Application (final Model)	Applying model results in real-world contexts or new problems based on the ESD contexts.
		Phase 2: Engineer
Ideate	Pursue Solutions (hands-on modelling)	Formulating solutions to defined problems based on user needs and developing various ideas and potential solutions through technological design based on the ESD contexts.
Prototype	Explore the Question	Deeply exploring user questions based on modeling results and creating prototypes or initial versions of selected solutions, both physical and digital, based on the ESD contexts.
	Engage in Collaborative Activities	Collaborating with others on projects to develop product solutions in design modeling based on strong theoretical foundations related to the ESD contexts.
	Use Learning Technologies and Other Scaffolds	Using technology and other learning aids for product solutions based on the ESD contexts.
Test	Create Artifacts	Testing prototypes with users or in real contexts, then collecting feedback and conducting evaluations based on the ESD contexts.

The outlined learning framework consists of two main phases: scientists and engineers, each with specific sub-phases focused on ESD. In the "Scientist" phase, students begin by empathizing through observation to gather information about phenomena and user needs within ESD contexts. Then, they conducted experiments to deepen their understanding. In the "Define" subphase, students create initial models using tools like SageModeler and Canva, followed by verifying and applying these models to real-world problems related to ESD. The "Engineer" phase starts with ideation, where students formulate solutions to defined problems based on user needs and develop ideas through technological design. They explore user questions, create prototypes, and engage in collaborative activities to develop product solutions grounded in ESD principles. Finally, in the "Test" subphase, students test their prototypes in real contexts, gather feedback, and refine their solutions. This framework promotes critical thinking and creativity, while preparing students for complex challenges in sustainable development.

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Control Groups

The control group was treated with STEM Project-Based Learning (PjBL), a method that is usually conducted by science teachers. The STEM PjBL model is a learning approach that does not incorporate modeling activities in the classroom. Instead, it focuses on general issues related to climate change that culminate in product output. The primary difference in the intervention between the two groups lies in the implementation of the learning model. The integration of scientific modeling within the context of ESD at the real-world application level is a distinctive feature of the experimental group, whereas the control group only applies STEM project-based learning without any additional innovations. Table 2 provides a comprehensive overview of the learning steps in the inquiry model used in the control group.

Table 2
Learning Steps and Learning Activity of STEM Project Based Learning

Steps	Learning Activity
Reflection	Guide students into the context of problems, enabling them to understand and generate ideas for solutions.
Research	Facilitate discussions that may challenge and deepen the students' understanding of problem solving.
Discovery	Organize students into groups to analyze information and present their solutions to problems.
Application	Evaluate the products created by students, allowing them to integrate STEM concepts at this stage.
Communication	Share the results of the project to enhance communication skills related to problem solving.

Source: (Laboy-Rush, 2015; Putri & Dwikoranto, 2022)

The learning process consists of five key steps: reflection, research, discovery, application, and communication, each designed to enhance students' problem-solving abilities within a collaborative framework (Laboy-Rush 2015; Putri & Dwikoranto 2022). In the Reflection step, students are guided into the context of specific problems, which helps them to understand the issues at hand and generate ideas for potential solutions. This foundational understanding is further developed during the research phase, where discussions are facilitated to challenge students' perspectives and deepen their comprehension of the problem solving process. Following this, the Discovery step involves organizing students into groups, allowing them to analyze information collaboratively and present their proposed solutions to the identified problems. In the application phase, students evaluate the products they have created, integrate STEM concepts into their work, and reinforce their understanding of the subject matter. Finally, the Communication step encourages students to share the outcomes of their projects, enhancing their communication skills and fostering a collaborative environment focused on effective problem-solving. This organized approach not only fosters critical thinking and collaboration but also equips students to effectively address real-world challenges. Project-based learning (PjBL) is widely accepted by educators and communities as an effective method of motivating students, particularly when teachers receive strong administrative support. In problem-based environments, students excel, driven by construction, social context, and community connections (Miller & Krajcik, 2019).

Data Collection Instrument

The assessment, intended to measure students' skills in scientific modeling, comprised 10 carefully designed questions. These questions assess students' abilities in scientific modeling, focusing on key aspects, such as: (1) Can the model explain all observations? (2) How can the model be used to predict the behavior of a system when manipulated in specific ways? (3) How does the model align with other concepts related to the functioning of the world and other scientific models? This approach not only establishes a connection between theoretical concepts and practical applications but also bridges the gap between abstract knowledge and real-world experiences. Furthermore, scientific modeling encourages students to actively construct their understanding of nature through observation, experimentation, and analysis (Wan et al., 2021). By refining their modeling skills, students can enhance their scientific literacy while acquiring transferable skills applicable to various disciplines, including logical reasoning, data interpretation, and effective communication. The assessment of students' scientific modeling skills incorporates aspects adapted from (OECD, 2022) and (Harline et al., 2021), tailored to the topic of climate change. Table 3 presents the aspects and indicators used in this study.

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Table 3
Aspects and Indicators of Scientific Modelling Skills

Aspect	Description	Indicator
Question	Identify the main question to be answered or the problem to be solved in the scientific process.	Given a weather model, students can formulate several questions based on the information from the fundamental concepts of weather
	By analyzing various climate models, such as weather, seasonal, and climate models, students formulate relevant questions that deepen their understanding of climate systems.	Given a seasonal model, students can formulate several questions based on information from the fundamental concepts of seasons
Plan	Plan the methods, steps, and resources needed to answer the question or solve the problem.	Given a climate model, students can formulate several questions based on the information from the fundamental concepts of climate.
	Identify critical challenges linked to climate change, such as the consequences of fossil fuel consumption, changes in land use, and the impact of policy choices.	Given a model of annual climate change factors, students can analyze issues related to the scientific model of the factors causing climate change
Build	Develop or construct the model, experiments, or instruments needed to answer the question or solve the problem.	Using a model of global greenhouse gas emissions, students can explain how human activities, particularly the combustion of fossil fuels, lead to higher concentrations of greenhouse gases in the atmosphere
	Builds the capacity to understand and communicate the interconnected nature of human actions, carbon cycles, and climate outcomes	Given a carbon cycle diagram, students can model how changes in this cycle can affect the global climate balance
Test	Conduct trials or experiments to obtain data and analyze the results according to the established plan.	Given a model of the impacts of climate change, students can explain the effects of rising sea levels
	fosters an understanding of the interconnectedness of climate change, agriculture, and food security, equipping students to address real-world challenges	Using a model that illustrates the impacts of climate change, students can describe how rising sea levels affect agriculture.
Revise	Review and improve the model, experiments, or processes based on the results to enhance accuracy or effectiveness.	Given a model of the effects of climate change on public health, students can explain the impact of the increase in weather-related disease occurrences
Share	Communicate the results, findings, or models to relevant audiences and receive feedback for further improvement.	Given a model of the effects of climate change, students can explain the impact on food security

The instrument designed to assess scientific modeling skills was subsequently validated, which included both content and construct validation processes (Ulya & Rosnawati, 2024). The content validity evaluation showed that all items in the question achieved an Aiken score (V) higher than .76, which confirms that all items are valid. To evaluate the validity of the construct, the questions were administered to ninth-grade students who had completed 2 years of lower secondary education. The construct validity test using the Rasch model analysis yielded a Cronbach's alpha value of .61, suggesting that the instrument is reliable. Although this Cronbach's alpha value indicates reasonably good reliability, further analysis revealed that the instrument has an explained variance value of 39.1%. The Eigenvalue was satisfactory, as it did not exceed the threshold of 3 (Mokshein et al., 2019). Meanwhile, the unexplained variance ranges from 7.80% to 13.10%. This indicates that the instrument is effective in measuring scientific modeling skills (Fisher, 2018). The essential unidimensionality (Rasch/common variance) was 62.8%, confirming that the instrument effectively measured a single construct. Before learning began, the students worked on the pre-test questions for scientific modeling skills for 100 minutes. After the learning was completed, the students answered the post-test questions for scientific modeling skills for 100 minutes. Further analysis of the data showed that the average total score for the 108 participants was within a maximum score of 100 and a minimum score of 56.8. The reliability of the instrument based on model analysis indicated a real RMSE value of 1.01 and a person reliability of .43. For the items, reliability demonstrated a very good value with an item reliability of .98. Although the person reliability value was relatively low, the overall psychometric analysis confirmed that the instrument remained valid and reliable for assessing students' scientific modeling skills, particularly at the group level. A high item reliability score reflects a well-constructed and consistently functioning set of items that align with the intended constructs.

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The instrument also showed acceptable item fit indices and logical progression of item difficulty, which supports its construct validity. The relatively lower person reliability may be attributed to the homogeneity of the sample or the range of abilities of the participants. However, this does not undermine the instrument's ability to detect significant differences between the experimental and control groups, as demonstrated by quasi-experimental findings. Therefore, the instrument is considered appropriate for research purposes in educational settings, especially when examining group-level learning outcomes in interventions related to STEM and sustainability education. In general, this instrument has proven valid and reliable for measuring scientific modeling skills.

Data Analysis

The analysis of the data from the scientific modelling skills test involved comparing the mean scores of the pretest and posttest. First, the normality distribution of the test data was assessed using the Shapiro-Wilk test. The Shapiro-Wilk test results for the pretest and posttest scores in both the control group (CG) and experimental group (EG) indicated $p > .05$, confirming that the data followed a normal distribution. Furthermore, the Levene test was conducted to evaluate the homogeneity of variance for the pretest and posttest scores in CG and EG, yielding $p > .05$, which indicated that the data were homogeneous. Parametric statistical tests were used to analyze the differences in scientific modeling skill scores between the CG and EG.

Additionally, a paired sample *t*-test was performed to assess the differences in average scores between the pretests and posttests for each aspect of scientific modeling skills in both the control group (CG) and the experimental group (EG). An independent sample *t*-test was also conducted to evaluate the differences in the average post-test scores between the CG and EG for each aspect of scientific modeling skills. The effect size for each aspect of scientific modelling skills in CG and EG was analysed using Cohen's Effect Size (Cohen, 1988).

Research Results

The STEM MDT was applied to the experimental group (EG), while STEM PjBL was used in the control group (CG) during science instruction. Before the start of the learning process, students completed pretest questions, and at the conclusion of the instruction, answered posttest questions. The pretest scores reflect the students' scientific modeling skills before the intervention, whereas the posttest scores offer insight into their scientific modeling skills after the implementation of the STEM MDT. Table 4 presents the descriptive statistics for the pretest and posttest scores of scientific modeling skills.

Table 4
Descriptive Statistics of the Pretest and Posttest

Aspect	Group	*n*	*M*		*SD*		Minimum		Maximum	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post
Question the problem	CG	53	65.80	7.31	11.8	8.83	25	43.75	62.5	95
	EG	55	72.19	88.18	7.28	12.6	50	75	75	100
Plan the Solution	CG	53	56.84	62.76	14.2	14.77	25	43.75	43.75	100
	EG	55	69.04	79.02	11.74	13.09	25	75	77.5	100
Build the Solution	CG	53	65.09	73.11	11.06	14.17	37.5	50	75	100
	EG	55	72.54	88.18	7.10	12.60	50	75	81.25	100
Test Product	CG	53	62.03	67.86	13.19	17.43	37.5	50	75	100
	EG	55	72.02	81.69	8.56	12.09	50	75	77.5	100
Revise Product	CG	53	63.92	71.11	1.87	13.27	50	62.5	75	100
	EG	55	73.33	88.90	4.27	12.82	50	75	75.25	100
Share Product	CG	53	62.03	69.10	1.95	12.88	50	43.75	75	100
	EG	55	72.12	81.30	8.130	12.47	50	75	81.25	100

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Aspect	Group	*n*	*M*		*SD*		Minimum		Maximum	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post
Overall Mean	CG	53	62.62	69.04	12.01	13.56	37.50	48.96	67.71	99.17
	EG	55	71.87	84.54	7.85	12.61	45.83	75.00	77.96	10.00

Table 4 indicates that overall, the mean post-test scores were higher than the pre-test scores in both the control group (CG) and the experimental group (EG). This pattern was also evident in each aspect of scientific modeling skills, where the average post-test scores surpassed the pre-test scores in both groups. However, when comparing the overall average pretest and posttest scores between CG and EG, the average score in EG was markedly higher than in CG. This disparity can be attributed to the different interventions that were implemented in each group. In CG, the intervention focused on STEM learning without integrating the aspects of modeling and ESD. In contrast, the EG intervention used the STEM MDT model, which emphasizes scientific modeling skills and ESD, incorporating the social, environmental, and economic dimensions. These differing pedagogical approaches resulted in variations in the enhancement of scientific modeling skills, culminating in higher average scores in the EG than in the CG. Additionally, a paired sample *t*-test was used to analyze the mean scores from the pretest and posttest, determining the differences in average scores for each facet of scientific modeling skills in the control group (CG) and experimental group (EG) (see Table 5).

Table 5
Comparison of Improvement in Scientific Modelling

Aspect	Group	*N*	Paired Sample *t*-test		Effect Size (ES) *(Cohen's d)*	
			t-value	*p*-value	Point Estimate	Interpretation
Question the problem	CG	53	-2.47	.02	.34	Small
	EG	55	-7.58	<.01	1.02	Large
Plan the Solution	CG	53	-2.13	.04	.29	Small
	EG	55	-6.24	<.01	.84	Large
Build the Solution	CG	53	-4.57	.00	.63	Moderate
	EG	55	-11.17	<.01	.94	Large
Test Product	CG	53	-2.31	.03	.32	Small
	EG	55	-6.16	<.01	.75	Moderate
Revise Product	CG	53	-3.61	.00	.50	Small
	EG	55	-11.95	<.01	1.16	Large
Share Product	CG	53	-3.71	.00	.51	Moderate
	EG	55	-5.75	<.01	.72	Moderate
Overall Mean	CG	53	-3.13	.00	.43	Small
	EG	55	-8.14	.01	.91	Large

The findings presented in Table 5 of the paired sample t-test reveal that the pretest-posttest scores for each aspect of scientific modeling skills in both the control group (CG) and the experimental group (EG) showed significant differences ($p < .05$), except for the aspect of planning and implementing the solution in CG, which was not significant ($p > .05$). In terms of effect size (ES), it is noted that in EG, three aspects fall into the very large category and one aspect falls into the large category, while in CG, three aspects fall into the moderate category, and one aspect falls into the small category. Overall, the effect size (ES) in the experimental group (EG) was greater than that in the control group (CG), indicating that the STEM MDT learning model intervention in EG had a more significant positive impact on scientific modeling skills than the STEM PjBL learning intervention in CG. Furthermore, an independent sample *t*-test was performed to analyze the average post-test scores and determine the significance of the differences between the EG and CG (Table 6).

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Table 6
Independent t-test of Scientific Modelling

Aspect	Group	*n*	Independent Sample *t*-test (Sig.)		Effect Size (ES) *(Cohen's d)*	
			t-value	*p*-value	Point Estimate	Interpretation
Question the problem	CG	53	-6.18	< .001	.84	Large
	EG	55				
Plan the Solution	CG	53	-3.85	< .001	.52	Moderate
	EG	55				
Build the Solution	CG	53	-3.25	< .001	.92	Large
	EG	55				
Test Product	CG	53	-3.97	< .001	.54	Moderate
	EG	55				
Revise Product	CG	53	-6.48	< .001	.88	Large
	EG	55				
Share Product	CG	53	-4.78	< .001	.65	Moderate
	EG	55				
Overall Mean	CG	53	-4.75	< .001	.73	Large
	EG	55				

Table 6 indicates that there were significant differences ($p < .05$) in post-test scores between the experimental group (EG) and the control group (CG) in all dimensions of scientific modeling skills. These results imply that the STEM MDT intervention in the EG is more effective than the intervention in the CG for improving scientific modeling skills. The effect size (ES) analysis shows that three aspects are classified as large, whereas three aspects are categorized as moderate. The STEM MDT provides students with the skills necessary for engaging in scientific modeling and planning alternative solutions, thus facilitating their training in the implementation of these solutions. In summary, these findings highlight that STEM MDT significantly enhances students' scientific modeling skills in comparison to the interventions utilized in CG.

Discussion

The findings of this study revealed a significant improvement in scientific modeling skills, particularly in the experimental group (EG) that received the STEM Modelling Design Thinking (STEM MDT) intervention. Both the control group (CG) and the EG showed gains from pre-test to post-test, yet the improvement was markedly higher, confirming the intervention's effects. Analysis in six dimensions of modeling skills demonstrated statistically significant improvements in the EG, with three aspects achieving a 'very large' effect size (ES > .8), one categorized as "large," and an overall effect size of .91 that contrasts sharply with the CG's moderate ES of CG of .43 (Cohen, 1988). These results underscore the positive and robust impact of the STEM MDT model in developing students' scientific modeling competencies (Krell & Krüger, 2016).

A closer look at posttest performance confirms that gains occurred across all components of modeling assessed in this study (Aiman & Hasyda, 2020; Alrawili et al., 2020; Miller et al., 2020). The success of the STEM MDT model can be attributed to its structured integration of design thinking principles with authentic scientific modeling practices, creating a more engaging, iterative, and applied learning environment (Donovan & Bransford, 2005). These outcomes align with previous literature advocating STEM-based, project-oriented, and inquiry-driven pedagogies to improve modeling proficiency. Furthermore, the artifacts illustrate a clear improvement path, evolving from rudimentary models with two to three variables into more sophisticated representations that integrate additional key variables (e.g., carbon emissions and rainfall patterns), intricate causal relationships, and evidence-based refinements. These iterations contributed to deeper scientific explanations and more dynamic system-based reasoning, although some students still required scaffolding to fully articulate their understandings (Bielik et al., 2018; Chiu & Lin, 2019).

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The iterative nature of the modeling process was pivotal in helping students refine their conceptual understanding, confront misconceptions, and internalize complex scientific ideas. This process supports the assertion that effective inquiry instruction should model scientific thinking (Crawford, 2000). The STEM MDT framework offers a concrete structure for classroom implementation, emphasizing the lived experience of modeling development over abstract theoretical critiques (Chiu & Lin, 2019). The involvement of the students in the design thinking phases (empathizing, defining, ideating, prototyping, and testing) was particularly visible in their sustainable housing projects (Dam & Siang, 2025; Mundy et al., 2024). These tasks prompted students to address climate-related issues, incorporating principles of ESD such as material sustainability, environmental impact, and social responsibility (Sutinah et al., 2024). Educators observed that students showed increased engagement and curiosity while actively investigating real-world issues, which enhanced their comprehension of sustainability challenges within STEM-based learning, which incorporates scientific modeling related to ESD topics (Van Driel & Verloop, 2002b).

The significant difference in effect sizes between the EG and CG further validates the capacity of the design thinking model to enrich scientific modeling skills. The integration of ESD within the STEM MDT framework allowed students not only to engage in modeling tasks but also to reflect critically on complex socio-environmental systems. As a result, students developed stronger competencies in scientific reasoning, problem solving, and innovation, which are essential for navigating 21st century challenges. Supporting this evidence, research by Yalçın & Erden (2021) in STEM education indicates that the application of data obtained from research diaries significantly enhances children's communication and interaction skills, fosters peer learning, promotes cooperation, boosts self-confidence, instills a sense of responsibility, encourages problem-solving and idea generation, and improves empathy skills.

Integrating ESD in Science Education through STEM MDT

Integrating ESD into science learning through scientific modeling is crucial for transforming abstract concepts into tangible understandings. At the practical application level, this integration serves as an essential intervention to motivate students to comprehend and analyze complex sustainability issues while simultaneously developing viable solutions through structured modeling processes (Griffith & Lechuga-Jimenez, 2024; Hebebci & Usta, 2022). Within the context of ESD, these phases holistically address the environmental, social, and economic dimensions (UNESCO, 2024). Specifically, the initial empathization phase involves students observing real-world phenomena, gathering initial insights, and identifying stakeholder needs through direct observation and interaction. At this stage, students are encouraged to investigate sustainability issues from multiple perspectives, encompassing economic, social, and environmental aspects. Internationally, there is increasing emphasis on fostering competency development through ESD. Scholars, such as Rieckmann 2022), have identified eight core sustainability competencies essential for advancing sustainable development, particularly within sustainability science programs. Among these competencies, systems thinking is emphasized as essential. It encompasses the ability to identify and understand relationships, analyze complex systems, grasp how systems are interconnected across different fields and scales, and navigate uncertainty. Within systems thinking, scientific modeling is employed to interconnect concepts and subconcepts into a coherent whole (Brundiers et al., 2021; Rieckmann, 2022). In the STEM MDT learning approach, the empathizing phase specifically involves observing natural phenomena and translating these observations into environmental, social, and economic aspects.

The empathize phase specifically involves students who observe natural phenomena and translate these observations into the environmental, social, and economic dimensions. Subsequently, in the define phase, students formulated a structured plan based on their observational findings, clearly identifying core problems that are contextually relevant and sustainable. This planning stage serves as a foundation for strengthening the initial modeling framework, allowing students to connect preliminary data with underlying scientific concepts related to observed issues. The modelling phase represents the core of scientific modeling skill development, in which students construct conceptual models through scientific reasoning and link various elements within complex systems (McNeill et al., 2004; Zuhri & Wilujeng, 2023). Initial models may take the form of diagrams, schemes, or simple physical representations illustrating relationships among variables such as temperature, humidity, and rainfall within a local climate system (Bamberger & Davis, 2013; Van Mil et al., 2013). After constructing the initial model, students proceeded to develop alternative solutions and assess the feasibility of the model through preliminary simulations or discussions, requiring divergent thinking and the synthesis of multiple scientific solutions (Alonzo et al., 2022; Berland & McNeill, 2010; Schwarz et al., 2009). In the prototype phase, the conceptualized model is transformed into a tangible prototype or a concrete model that can be tested. This stage allows students to revise their initial models based on experimental results or functional tests, thereby deepening their understanding of

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the interconnections between scientific concepts and processes (Schwarz et al., 2009). Finally, in the test product phase, the completed product was evaluated to determine the effectiveness of the model in explaining or solving the identified problem. This phase also includes a sharing process in which students present their model development outcomes to an audience or community and receive feedback (Buntha et al., 2024).

Empirical evidence from the EC and CG classrooms, as presented in Table 5, supports each phase of the STEM MDT approach, demonstrating significant impacts on various aspects of scientific modeling skills. The processes involved in scientific modeling skills not only lead to the creation but also serve as a progressive learning sequence, encompassing the formulation of questions, design of conceptual models, development of prototypes, and communication of results through scientifically supported modelling activity. This comprehensive process reflects the integration of scientific modeling within an educational context oriented toward sustainability (ESD). The STEM MDT offers significant advantages that substantially enhance students' educational experiences. First, it combines various disciplines of science, technology, engineering, and mathematics within a design thinking framework, allowing students to grasp the interconnectedness of these fields (Bosman & Eom, 2019; Dam & Siang, 2025; Fan & Yu, 2017). This approach emphasizes problem solving by encouraging students to identify and address real-world issues relevant to social, economic, and environmental contexts, thus developing critical and creative thinking skills.

Additionally, STEM MDT focuses on cultivating modeling skills and empowering students to create conceptual representations of complex systems, an essential competency in scientific and engineering practices. The project-based learning component immerses students in hands-on experiences, deepening their understanding and knowledge retention (Baran et al., 2021; Maida, 2011; Miller & Krajcik, 2019). Furthermore, it promotes active student engagement, boosting motivation and interest in STEM subjects, while fostering collaboration and communication skills through teamwork. By integrating the principles of ESD, students learn to consider the environmental, social, and economic impacts of their solutions and prepare them to become responsible future leaders (Riess et al., 2022). The iterative and reflective nature of the process encourages learning from mistakes and refining solutions, thus cultivating a lifelong learning mindset. Supported by empirical evidence demonstrating significant improvements in modeling skills and systems thinking, the STEM MDT approach effectively equips students to address today's complex, interconnected global challenges.

Through the integration of real-world problems, interdisciplinary content, and reflective practices, students can not only construct meaningful scientific models but also apply these models to analyze environmental, social, and economic issues aligned with the Sustainable Development Goals (SDGs). This capacity to transfer knowledge across contexts signifies a deeper understanding of science as a tool for informed decision making and societal contributions. Integrating STEM Design Thinking with ESD is essential for equipping students with competencies to address global issues such as climate change and environmental degradation. This approach aligns with PISA frameworks that emphasize the application of scientific knowledge and evidence-based reasoning in real-world contexts (OECD, 2025). It fosters systems thinking and cross-cutting competencies, such as ethical decision making and data literacy, through pedagogical strategies such as self-regulated learning (Demssie et al., 2023), service learning (Martn-Sánchez et al., 2022), and socioscientific issue integration(Van Der Veen, 2023). In the modeling process, students are guided to identify and analyze the interrelationships among variables, an essential aspect of systems thinking, enabling them to construct conceptual models that reflect the dynamic and interconnected nature of real-world phenomena. The use of outcome indicators to assess ESD implementation ensures progress toward sustainability competencies (Cebrián et al., 2021), while teacher capacity-building programs incorporating future studies help educators prepare students for uncertain and complex global realities (Khadri, 2022). Initiatives such as Smithsonian Science for Global Goals demonstrate how data-driven STEM education and science communication can engage students in solving real-world problems within their communities (Gibson et al., 2023). Ultimately, hands-on STEM projects and citizen science initiatives provide transformative experiences that not only enhance modeling skills but also prepare students to become responsible and informed global citizens (Batchelder et al., 2023; Greif et al., 2020; Miller & Krajcik, 2019; Rott et al., 2024). As students increasingly recognize the importance of sustainable development, educational institutions must adapt their curricula to integrate economic, social, and environmental issues, thus preparing students for future challenges (Zwolińska et al., 2022).

STEM MDT's Contribution to Sustainable Development Goals (SDGs)

This study makes a significant theoretical contribution to future-oriented science education by illustrating how the integration of ESD within the STEM MDT framework enhances both students' scientific modeling skills and their transformative competencies. The incorporation of design thinking phases in STEM MDT facilitates inquiry-

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based and modeling-based learning that aligns with the core science and engineering practices articulated in the Next Generation Science Standards (NGSS), including developing and using models, constructing explanations, and designing solutions. This approach reflects and extends the work of Schwarz et al. (2009), who conceptualize scientific modelling as an essential epistemic practice by applying it to authentic and socially relevant sustainability contexts. Furthermore, the model encourages the development of transformative competencies, such as systems thinking, anticipatory thinking, and agency to sustainable action, as emphasized in the OECD Learning Compass 2030 and UNESCO's ESD for 2030 Roadmap (OECD, 2022; Rieckmann, 2022; UNESCO, 2024).

These competencies represent an educational shift beyond foundational scientific literacy, fostering students' capacity to integrate engaging with complex socio-environmental problems and to co-create sustainable solutions. Such integration supports the cultivation of not only disciplinary knowledge, but also the values, skills, and attitudes necessary for navigating and shaping a sustainable future. In doing so, the intervention directly contributes to the realization of SDGs, particularly Target 4.7, in quality education by offering an instructional innovation that integrates STEM and ESD principles to enhance students' scientific modelling skills. This target advocates education that promotes sustainable development, including the development of competencies needed to address global challenges. The intervention also aligns with Target 13.3, which calls for improved education and awareness of climate change mitigation and adaptation by providing students with contextually relevant, solution-oriented learning experiences grounded in local environmental issues. As students engage in these processes, they not only develop scientific modelling abilities but also internalize pro-environmental values and behaviors that reflect a scientific attitude toward sustainability. They also support basic scientific literacy, which includes the ability to understand scientific phenomena, construct explanations, and use evidence to inform reasoning; the intervention promotes transformative competencies as outlined in sustainability education frameworks (McNeill & Krajcik, 2008; Van Mil et al., 2013). These include systems, anticipatory, normative, collaboration, and self-efficacy. By incorporating STEM-Design Thinking and ESD principles, the learning design fosters students' capacity to act on sustainability challenges, empowering them to become proactive change agents in their communities.

Research Contributions

Practically, this study contributes by providing educators with a clear and structured instructional framework that progressively develops students' scientific modelling skills from initial observation and conceptualization to prototype creation and communication of scientifically supported solutions. Furthermore, the findings offer practical implications for teachers and educational professionals by demonstrating the feasibility and effectiveness of integrating STEM MDT in science education. This integration fosters motivation, engagement, and collaborative skills, preparing them to effectively analyze, model, and solve real-world sustainability problems (Ardianti et al., 2020). Additionally, empirical evidence from classroom implementation supports the STEM MDT approach, highlighting significant improvements in students' modeling skills and systems thinking competencies, thus equipping them to become responsible and capable future leaders in addressing global sustainability challenges.

These findings support previous research emphasizing the significance of incorporating STEM design thinking into science education focused on ESD to systematically improve students' skills (Hassan, 2023; He et al., 2023b; Hebebci & Usta, 2022). Evidence indicates that structured instructional frameworks, such as STEM MDT, can facilitate progressive learning from initial observation and conceptualization to the creation, testing, and communication of scientific modelling. This aligns with studies that demonstrate how developmentally suitable STEM interventions, including mobile applications and robotics kits, can foster essential modeling and computational thinking skills even in young learners (Kalogiannakis & Papadakis, 2020; Papadakis, 2019; Papadakis & Orfanakis, 2017; Yalçın, 2022). Furthermore, the current study is consistent with research in higher education that shows that interdisciplinary, sustainability-oriented STEM experiences enhance both the self-efficacy of preservice teachers and their understanding of complex environmental issues, particularly through design-based methodologies (Rico et al., 2021; Zhou et al., 2023). Our empirical findings extend this evidence to the secondary education context, demonstrating that STEM MDT can serve as a scalable and flexible approach to promote not only modeling skills but also systems thinking among students, which is essential for addressing real-world sustainability challenges (Demssie et al., 2023; Peretz, Dori, et al., 2023; York et al., 2019). By combining hands-on modeling with real-world ESD challenges, students actively engage in meaning-making, hypothesis testing, and refining their representations, an approach that aligns with the educational objectives outlined in the PISA 2025 science framework (OECD, 2025; Zhang et al., 2024). Therefore, the implementation of STEM MDT offers both pedagogical and epistemological connections between classroom learning and the competencies necessary to address future global challenges.

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This study makes several important contributions to STEM education. Validating a novel and effective pedagogical model for cultivating scientific modelling skills, demonstrating the added value of combining design thinking with science education, and providing practical strategies for integrating iterative, project-based learning into classroom practice. Moreover, it emphasizes the necessity of embedding ESD principles into STEM learning to foster critical and systems thinking (Sutinah et al., 2024; Tamir et al., 2023). In terms of practical implications, the STEM MDT intervention offers a replicable instructional framework that can enhance classroom engagement and promote student-centered activities (Motschnig & Holzinger, 2022). It also provides a valuable reference for teachers' professional development, particularly in training educators to facilitate modelling and design thinking processes in science lessons (Huang et al., 2022). From a curriculum perspective, this model supports the integration of interdisciplinary and sustainability-focused learning, aligned with current educational priorities (Kim et al., 2007). At the policy level, the findings support the need for the systemic encouragement of inquiry-based and design-oriented science education approaches, including the allocation of resources and training to scale such innovations (Cuevas et al., 2005). Future studies are encouraged to explore the applicability of this model in various scientific disciplines and school contexts, as well as to develop more sophisticated assessments of higher-order systems thinking and modelling competencies that may emerge from such interventions.

Innovative Pedagogical Framework for Advancing STEM Learning

Moreover, this study offers important contributions to the advancement of STEM education by validating a novel pedagogical framework, STEM MDT, which combines the epistemic practice of scientific modeling with the creative and iterative processes of design thinking. This integration not only facilitates students' understanding of scientific concepts but also fosters critical, systems-oriented reasoning that aligns with the contemporary frameworks of modeling-based and inquiry-based science education (Novak & Krajcik, 2019; Schwarz & White, 2005). In terms of practical implications, the STEM MDT intervention offers a replicable instructional framework that can enhance classroom engagement and promote student-centered activities (Motschnig-Pitrik & Holzinger, 2022). In terms of practical implications, STEM MDT provides a valuable foundation for teacher professional development, particularly in training educators to facilitate iterative modeling and design-oriented instruction in science classrooms (Huang et al., 2022). The model's emphasis on iterative construction, testing, and refinement reflects an authentic approach to science learning, bridging disciplinary knowledge with socio-environmental problem solving. From a curriculum development perspective, this model supports the integration of interdisciplinary, future-focused learning aligned with global education priorities and Sustainable Development Goals (Kim et al., 2007). At the policy level, the findings emphasize the need for systemic support to scale inquiry- and design-based science education, including adequate resourcing, curricular flexibility, and capacity-building initiatives (Cuevas et al., 2005). Future research should explore the transferability of this model across diverse scientific domains and educational contexts, as well as develop robust assessments to capture the emergence of higher-order modeling and sustainability competencies.

In addition to its contributions to STEM and ESD, this study offers valuable implications for science education by enhancing students' ability to interpret, construct, and critically evaluate visual data representation skills that are central to scientific literacy (L. Zhang et al., 2023). Through the STEM MDT framework, students engage in iterative modeling processes that require them to analyze and communicate information using visual tools, such as graphs, charts, and conceptual diagrams, thus supporting the development of graphical perception and data interpretation competencies (Cleveland & McGill, 1985; Lynch & Woolgar, 1990). This aligns with the increasing demand for visual data literacy in science education, particularly in ensuring that visual elements such as color maps are scientifically valid, accessible, and free from distortion, especially for students with color vision deficiencies (Crameri et al., 2020). Furthermore, by integrating modeling tasks within a structured and contextually meaningful instructional design, this study addressed the key factors influencing students' understanding of visual representations, such as cognitive load and prior knowledge (Cook, 2006). It also reinforces the idea that, while alternative forms of data representation can enhance conceptual understanding, they must be critically designed to avoid misinterpretation (Eisner, 1997). Therefore, STEM MDT contributes to science education not only by improving modeling skills but also by cultivating students' data literacy, visual reasoning, and critical thinking core competencies required to navigate complex scientific and real-world information.

Finally, it was established that the implementation of STEM MDT significantly boosts students' scientific modeling skills. Studies that compare the experimental group using the STEM MDT learning model with the control group implementing STEM PjBL indicate that incorporating ESD topics into the STEM MDT approach is more effective in

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improving students' scientific modeling skills. These findings reinforce those of previous studies, although some research has also reported that STEM learning based on design thinking generally has a positive impact on scientific modeling activities within the engineering design process (Atman et al., 2007). Additionally, integrating ESD into project-based learning contexts that relate to real-world scenarios offers students considerable motivational benefits. Intricate and diverse ESD topics, such as climate change, foster students' curiosity and motivate them to explore important issues from multiple perspectives. This approach inspires students to actively collect additional information, analyze the accuracy and relevance of the data, and construct persuasive arguments to solve problems through scientific modeling. Thus, this learning model not only enhances students' interest in learning but also prepares them to become responsible individuals capable of addressing and solving real-life problems sustainably.

Conclusions and Implications

Through rigorous data analysis and interpretation, this study provides robust empirical evidence that the STEM MDT model is more effective than STEM PjBL in enhancing students' scientific modeling skills. When examining the experimental and control groups separately, both groups showed improvements in their scientific modeling skills. However, the STEM MDT, which integrates ESD issues at the real world application level, contributes more positively to students' scientific modeling skills than conventional project-based STEM learning. The effects of this integration are apparent in the enhancement of students' capabilities to recognize issues, propose different solutions, and effectively execute those solutions in the context of ESD. This indicates that innovation in modeling-based learning and ESD is essential in science education to equip students with the various essential skills needed to tackle complex issues in the future and prepare them for PISA assessments.

The implications of this study indicate that the STEM MDT model can be a valuable instructional innovation in science education, particularly when grounded in real-world applications and sustainability-oriented learning. By embedding the principles of ESD, this approach fosters students' critical thinking, analytical reasoning, and synthesis skills, which are necessary to address global challenges and adapt to dynamic social changes. Therefore, educators and policymakers should consider adopting this model to promote adaptive, inquiry-based, and future-oriented science learning. Moreover, while the study demonstrated encouraging outcomes, it is important to interpret the results with caution. Specifically, the relatively low person reliability reported in the Rasch analysis suggests potential limitations to estimating individual students' ability levels with high precision. This may have affected the robustness of the conclusions drawn at the individual level. However, it is noteworthy that the instrument exhibited high item reliability and item separation indices, indicating that it was effective in distinguishing item difficulty and was suitable for making valid inferences at the group level. Future research may refine the assessment tools or employ additional measurements to enhance the reliability of individual level estimate.

Limitations and Future Research

This study provides significant contributions to advancing science education through the integration of STEM-MDT and ESD; however, several limitations must be acknowledged. First, the relatively small and localized sample size restricts the generalizability of the findings to larger populations. Second, the intervention was carried out over a short period of four weeks, which may not fully capture the long-term impact of the STEM MDT. Third, the study was conducted within a specific cultural and educational context, which can influence how the model is received and implemented in different regions or school systems. Future research is recommended to test the applicability of the STEM MDT model across diverse educational settings, extend the duration of the intervention, and incorporate more varied assessment methods to evaluate long-term learning outcomes and transferability. Fourth, while the Rasch analysis indicated acceptable item reliability and separation, the person reliability index was relatively low. This suggests that the instrument may have limited sensitivity in distinguishing students' abilities at the individual level. Therefore, caution is warranted when interpreting findings related to individual performance, as the measurement precision may be more robust at the group level than at the individual level. Future studies should consider enhancing the instrument's person reliability by increasing the number of items or improving item targeting to better capture individual differences.

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Declaration of Interest

The authors declare no competing interest.

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EFFECTIVENESS OF A GAMIFIED INTERACTIVE RESPONSE SYSTEM FOR ENHANCING PRIMARY SCIENCE EDUCATION

Yi Wen Lo

Abstract. *Primary school students of the digital generation often struggle to maintain motivation and engagement, especially under static and non-interactive teaching strategies, underscoring the need for more effective educational approaches. This quasi-experimental study examined whether integrating a gamified interactive response system, Blooket, into a sixth-grade natural science curriculum could enhance students' self-determined motivation and learning effectiveness. The experimental group (n = 52) completed online Blooket quizzes, while the control group (n = 52) took paper-and-pencil tests. Both were administered as formative assessments following the teaching sessions. Data were collected using a self-determined motivation scale and a learning effectiveness test. A self-determined motivation scale was developed specifically for this study, with strong construct validity and satisfactory model fit confirmed through exploratory and confirmatory factor analyses. The results indicated that Blooket significantly enhanced self-determined motivation and improved learning effectiveness in the experimental group. Additionally, students reported increased interest in learning and improved classroom dynamics. These findings suggest that gamified interactive response systems have the potential to enhance educational practices by effectively engaging students. Future research should examine the long-term effects and limitations of such systems across diverse educational contexts.*

Keywords: *gamified interactive response system, learning effectiveness, primary natural science education, self-determined motivation*

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Introduction

Digital technologies profoundly influence the new generation, shaping their interactions, learning habits, and preferences. Twenge (2017) has reported that American teenagers spend an average of 2.25 hours per day texting, 2 hours browsing the internet, and 1.5 hours playing digital games, underscoring the pervasive role of technology in their daily lives. Similarly, Apaydin and Kaya (2020) have observed that students interact with digital technologies from an early age, demonstrating high levels of technological fluency. While this proficiency has provided certain advantages in educational contexts, it has also posed challenges, such as difficulty maintaining attention and a tendency to prioritize immediate gratification over long-term goals (Prensky, 2001). To address these issues, it has been suggested that educators should adapt teaching strategies to align with students' preferences for quick information uptake, visual stimuli, and interactive learning experiences (Raja & Nagasubramani, 2018).

Learning is most effective when it incorporates active engagement, clear objectives, contextual relevance, and intrinsic interest (Bruner, 1961; Bransford et al., 2000; Quinn, 2005). Cultivating intrinsic motivation is a fundamental step in fostering active learning. Self-determination theory (SDT) provides a comprehensive framework for exploring intrinsic and extrinsic motivation. According to SDT, fulfilling learners' basic psychological needs—competence, autonomy, and relatedness—enhances self-determined motivation (Deci & Ryan, 1985, 2000). When learners exhibit higher levels of self-determined motivation, their overall motivation tends to shift toward intrinsic motivation, enabling them to engage more actively in their studies. This shift not only improves the effectiveness of learning but also establishes self-determined motivation as a critical factor for achieving successful learning outcomes. Therefore, this study aimed to identify educational strategies that could enhance self-determined motivation, aiming to address the learning challenges faced by the new generation of students.

Research Focus

Plass et al. (2015) have indicated that learners often exhibit heightened motivation during gameplay, and game-based learning has been widely recognized as a form of active learning (Chen, 2019). By integrating educational content with the engaging nature of games, digital game-based learning

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provides opportunities for students to play, experiment, make mistakes, and learn, fostering knowledge acquisition and cognitive development (Hwa, 2018). Recent studies have demonstrated that digital game-based learning environments can significantly enhance student engagement and learning outcomes across various subject areas. For example, the use of a 3D serious game to teach ancient Greek theatre has resulted in greater knowledge acquisition compared with traditional teaching methods (Papadakis et al., 2020), while integrating a game-development approach using App Inventor in computer science courses has enhanced students' programming skills and motivation through constructionist learning principles (Papadakis, 2020). However, while game-based learning and gamification share some overlapping characteristics, they represent distinct pedagogical approaches. Game-based learning involves the use of computer games explicitly designed for educational or training purposes, whereas gamification refers to the application of game elements—such as points, badges, and leaderboards—within non-game contexts to enhance motivation and learning outcomes (Liu et al., 2011; Werbach & Hunter, 2012).

Interactive Response Systems (IRSs) represent another innovative pedagogical tool. These systems enable students to provide immediate feedback via devices such as smartphones and tablets, thereby enhancing engagement, motivation, and classroom interaction (Fies & Marshall, 2006; Slain et al., 2004). Since their introduction in the 1950s, IRSs have demonstrated effectiveness in improving academic performance and pass rates (Mazur, 1997; Poulis et al., 1998). Modern online IRSs address hardware limitations of earlier models, offering enhanced functionality and reducing educators' preparation time (Green, 2014). Furthermore, incorporating game elements into Gamified Interactive Response Systems (GIRSs) helps mitigate the motivational decline associated with prolonged use of traditional IRSs (Aguilar et al., 2018).

A notable example of GIRSs is the Blooket platform, which incorporates game elements into its interactive features. Blooket's built-in game modes use mechanisms such as accruing points through correct answers, badges, and rankings to engage students in gamified learning rather than traditional gaming. Features such as immediate feedback on performance, pace regulation, and avatar recognition on leaderboards align closely with SDT principles, affirming competence, autonomy, and relatedness. These attributes make gamified tools particularly effective in fostering self-determined motivation. Moreover, the inherent structure and motivational qualities of games align well with these principles.

Despite the numerous advantages of GIRSs, prior research has predominantly focused on high school or university courses. This focus was largely due to the limitations of early systems in terms of hardware and the technological proficiency of students. In recent years, improvements in hardware availability and students' technological capabilities at the primary school level have created new opportunities for research. This study examined the impact of a GIRS on learners' self-determined motivation and learning effectiveness in the primary school natural science curriculum, offering insights into educational strategies for enhancing student engagement and attention.

Research Aim and Research Questions

This study aimed to examine the effectiveness of integrating the GIRS—Blooket into a sixth-grade natural science curriculum in enhancing students' self-determined motivation and learning effectiveness. Specifically, this study was guided by the following research questions:

1. Does the integration of Blooket into formative assessment improve students' self-determined motivation and learning effectiveness compared to paper-and-pencil tests?
2. What are the perceptions of the experimental group regarding the GIRS-integrated teaching approach?

Research Methodology

Research Design

This study employed a quasi-experimental research design using the sixth-grade natural science curriculum unit "Changes in Weather" as the teaching material. The curriculum was implemented over four weeks in November 2024, with three lessons per week, totaling 12 lessons. Both the experimental and control groups were taught by the same teacher to ensure consistency in the teaching practice. Except for the formative assessment method, all lesson materials, learning activities, lesson sequences, and teaching methods were identical for both groups.

At the end of each subunit within the "Changes in Weather" curriculum, the experimental group (two classes) completed formative assessments using the online gamified platform Blooket for approximately 15 minutes per

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week. In contrast, the control group (two classes) took paper-and-pencil tests, each comprising 20 multiple-choice questions, as formative assessments. The test items for both groups were identical.

In the experimental group, the teacher first created a question set, selected a game mode, and set the duration for each game session. A unique game ID was then generated, which students entered to join the game. Students were able to create their own nicknames and choose avatars, thus fulfilling their psychological need for autonomy as defined by SDT. During the game, the competition results were projected in real-time onto the interactive white-board, enhancing the sense of competition. To win the game, students were required to answer questions correctly. Figure 1 shows a student answering a science question using the Blooket platform on a tablet device. Immediate feedback was provided after each response. Upon completion of the game, the top three rankings were displayed on the interactive whiteboard, thereby satisfying students' psychological needs for competence and relatedness, consistent with SDT. Figure 2 presents the top three performers projected onto the interactive whiteboard at the end of the Blooket game. To ensure anonymity, students' nicknames were blurred.

Figure 1
Students' Response Interface on the Blooket Platform

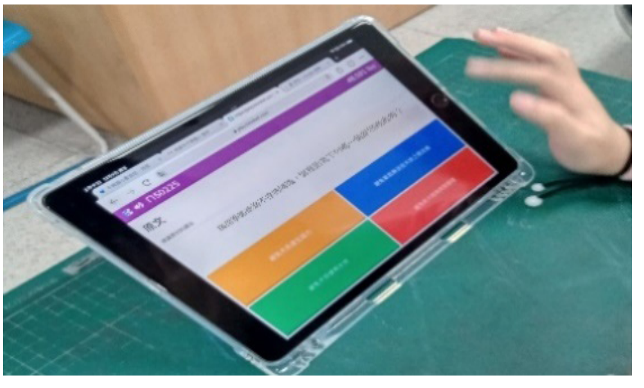
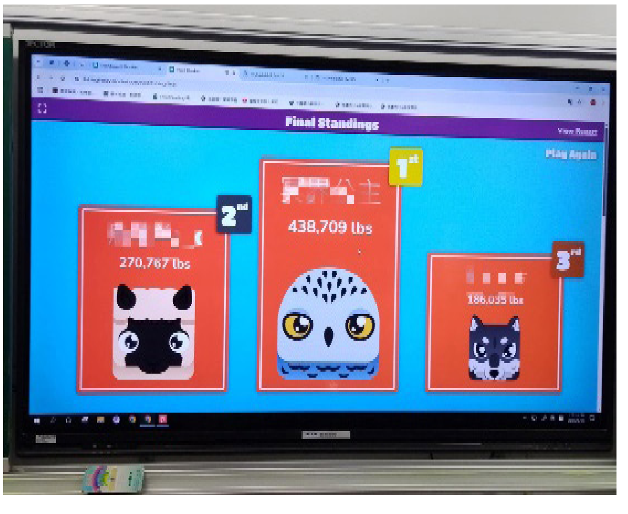


Figure 2
Top Three Performers' Avatars on the Interactive Whiteboard



Additionally, teachers could review the platform's analytical reports after the game to assess students' response accuracy and use the information to guide teaching adjustments, as illustrated in Figure 3. The results of paper-and-pencil tests administered to the control group also served as a tool for teachers to evaluate teaching effectiveness; however, the systematic charts provided by Blooket were easier to interpret.

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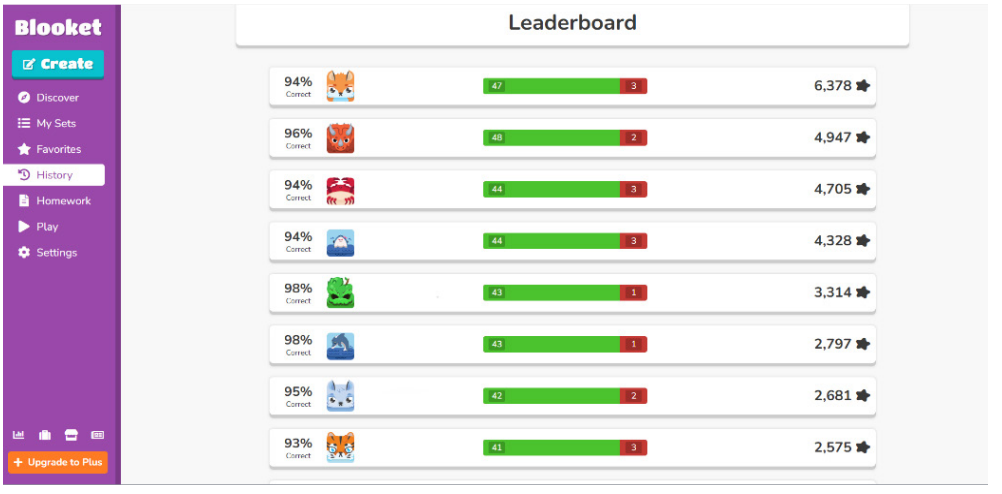
Figure 3
Students' Accuracy and Performance Rankings from the Blooket Platform Report



A pretest–posttest design was adopted, wherein students in both groups completed measures of self-determined motivation and learning effectiveness before and after the intervention to examine changes attributable to variation in formative assessment methods. Learning effectiveness was measured using the Changes in Weather Test, developed specifically for this study. Self-determined motivation was assessed through the "Self-Determination Motivation Scale," validated through exploratory and confirmatory factor analyses, demonstrating strong reliability and validity.

Analysis of covariance (ANCOVA) was used to compare post-intervention differences between groups, while statistically adjusting for pretest scores. Independent samples *t tests* were conducted to assess group differences in self-determined motivation. Additionally, a Blooket Attitude Questionnaire was administered to the experimental group to assess students' perceptions of integrating Blooket into the teaching process.

Participants

This study used convenience sampling to select four sixth-grade classes from the same school. The experimental group comprised two classes with a total of 52 students (26 boys and 26 girls), while the control group consisted of two classes with 52 students (25 boys and 27 girls). All students were drawn from heterogeneously grouped classes that were formed through the school's standard random assignment process, ensuring comparable distributions in academic performance, abilities, and backgrounds. Therefore, although convenience sampling was employed, differences in students' prior experience and background across classes were minimal. Both groups were taught by the same teacher to minimize potential researcher-induced bias in the experimental implementation. All research procedures related to the experimental intervention were clearly communicated to participants and their legal guardians, including the purpose, content, and procedures of the study, as well as the voluntary nature of participation. There were no academic risks associated with participation. Anonymity was preserved, and participants' privacy and data confidentiality were strictly protected.

Additionally, one sixth-grade class with 25 students was selected for the development of the Changes in Weather Test. Convenience sampling was also used to recruit three additional primary schools to support the development of the Self-Determination Motivation Scale. Because researchers have recommended a minimum sample size of $N \geq 200$ for both exploratory factor analysis and confirmatory factor analysis to ensure stable and replicable factor structures (Comrey & Lee, 1992; de Winter et al., 2009; Kyriazos, 2018), the preliminary scale was administered to 335 fourth- and fifth-grade students at one school, resulting in 325 valid responses (response rate was 97.01%). Item analysis and exploratory factor analysis were conducted on this dataset. At the other two schools, 500 fourth- and fifth-grade students were recruited, and 458 valid responses were collected (response rate was 91.6%), on which confirmatory factor analysis was conducted. The questionnaire data collection for scale development included anonymous and low-risk items related to general learning motivation. It was conducted in accordance with approved ethical guidelines, and anonymity was strictly maintained.

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Research Instruments

Self-Determination Motivation Scale

In the past, scales developed based on SDT have been predominantly applied in areas such as sports (Ntoumanis, 2001; Mallett et al., 2007), special education (Garn et al., 2010; Lee et al., 2010), and healthcare (Williams et al., 1998). There has been limited exploration of motivational changes associated with technology integration in teaching. Therefore, a self-determination motivation scale suitable for primary school students was developed independently. This scale is grounded in the motivational categories of SDT and includes modifications to the motivational beliefs section from the Motivated Strategies for Learning Questionnaire (MSLQ), originally developed by Pintrich and De Groot (1990). The three motivational beliefs in the MSLQ—expectancy components, value components, and affective components—reflect the motivational types defined in SDT: expectancy components correspond to the psychological need for competence; value components resemble identified regulation; and affective components focus on negative emotions (test anxiety), which are linked to amotivation. For suitability to primary school students, the motivational beliefs section of the MSLQ was adapted into age-appropriate questions, and items not relevant to their everyday contexts were omitted, leading to the creation of the preliminary items for the self-determination motivation scale. The preliminary scale comprises 31 items and employs a 5-point Likert scale, ranging from "strongly agree" (5 points) to "strongly disagree" (1 point).

Item Analysis

In this study, the top 27% of the highest scores and the bottom 27% of the lowest scores were selected as extreme groups. After re-grouping, independent samples *t* tests were conducted to assess item-level discrimination. One item with a *t* value of 2.85 was removed, while the remaining items showed *t* values ranging from 4.13 to 12.78 ($p < .001$), demonstrating strong item discrimination (Shiffler, 1988).

Exploratory Factor Analysis

Kaiser (1974) proposed that before factor analysis can begin, the Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) and Bartlett's test of sphericity should be used to determine whether the items are suitable for factor analysis. The KMO value of this study was .86, and the χ^2 value of Bartlett's test of sphericity was 3072.43 ($df = 325$, $p < .001$), indicating a statistically significant result. According to Kaiser (1974), a KMO value higher than .8 indicates that a scale is suitable for factor analysis.

The principal component extraction method was used to extract factors, and the maximum variation method via orthogonal rotation was used to analyze the factors. In the first factor analysis, according to the suggestion of Tabachnick and Fidell (2013), questions with factor loadings of at least .4, and preferably above .5, were considered acceptable. Thus, two questions with factor loadings lower than .4 were deleted, and one question with factor loadings spanning two factors was also deleted. For the second factor analysis of the remaining 25 questions, a total of six factors were extracted. In order to facilitate the study and analysis, these six factors were classified according to the question meaning and motivation type as follows—Self-Efficacy (SE, five items), Identified Regulation (IR, seven items), External Regulation (ER, three items), Introjected Regulation: External Expectation (IREE, three items), Introjected Regulation: Self-Demands (IRSD, three items), and Amotivation: Test Anxiety (ATA, four items). The factor loadings of each item ranged from .47 to .75, and the eigenvalues of the six factors ranged from 4.50 to 23.21, all higher than 1. The six factors could explain 60.69% of the total variation of the total scale, which was higher than the requirement of 60%, indicating that the scale had good construct validity (Hair, 2010). In the reliability analysis, the internal consistency—as indicated by Cronbach's α values of .80, .86, .70, .71, .73, and .77 for each factor, and .84 for the total scale—demonstrates good overall reliability (George & Mallery, 2003).

Confirmatory Factor Analysis

Following the analyses that shaped the formal scale, the scale was administered to a second group of 500 subjects, from which 458 valid scales were recovered. Subsequently, confirmatory factor analysis was conducted using Amos 29.0 statistical software to test the construct validity of this scale. The mean scores of the questions on the formal scale ranged from 2.98 to 4.41, with standard deviations ranging from 0.84 to 1.36. The kurtosis

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ranged from -1.21 to 1.03, and the skewness ranged from 0.02 to -1.26, with the absolute values of skewness and kurtosis both being less than 2, indicating a normal distribution. Therefore, structural equation modeling (SEM) analysis was adopted.

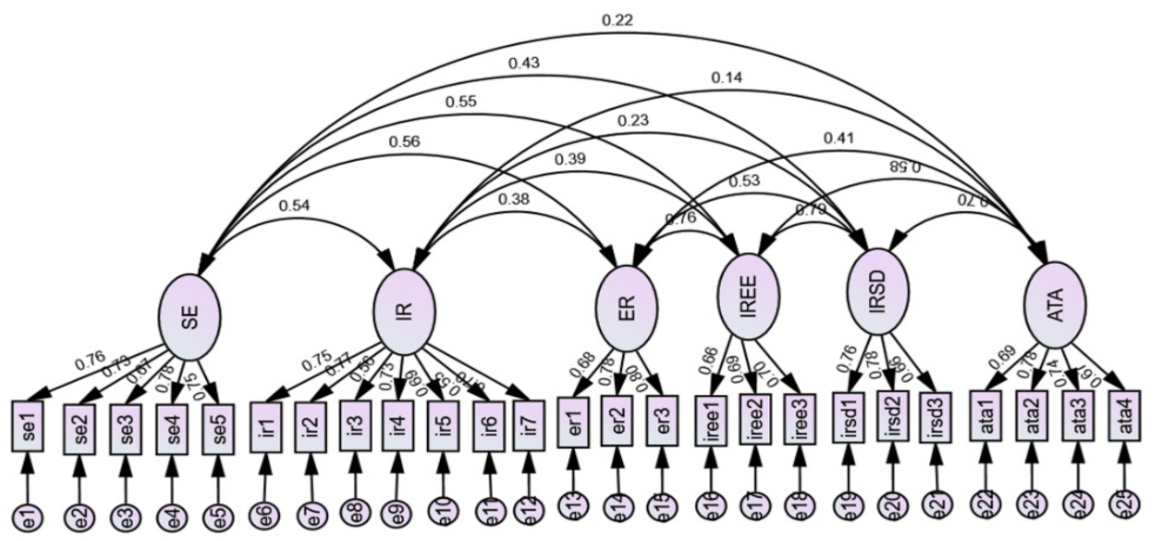
Next, the maximum likelihood method was used to perform confirmatory factor analysis on the scale items of different latent dimensions. Factor loadings ranged from .55 to .80. The overall model fit was tested using the Absolute Fit Indices, Incremental Fit Indices, and Parsimonious Fit Indices. Accordingly, the study employed the fit indices standards of Bagozzi and Yi (1988) and Hu and Bentler (1999) to conduct these tests, with the results shown in Table 1.

Table 1
Model Fit Indices for the Confirmatory Factor Analysis

Fit index (cutoff criteria)	Test value	Fit index (cutoff criteria)	Test value
χ^2 (p > .05)	544.99 (p < .05)	NFI > .90	.89
df	260	IFI > .90	.94(fit)
χ^2 / *df* < 3.00	2.10(fit)	TLI > .90	.93(fit)
RMSEA < .08	.05(fit)	CFI > .90	.94(fit)
SRMR < .08	.05(fit)	PNFI > .50	.77(fit)
GFI > .90	.92(fit)	PGFI > .50	.82(fit)
AGFI > .90	.89	CN > 200	251(fit)

From Table 1, it is evident that most indicators meet the standards. The significant χ^2 test result (p < .001) rejects the null hypothesis; however, this may be attributable to the potential inflation of the χ^2 value when the sample size is large. This was clarified using the Bollen-Stine p-value correction method. The AGFI indicator is sensitive to the estimated number of parameters; thus, MacCallum and Hong (1997) recommend relaxing the standard to greater than .8. Additionally, Ullman (2001) pointed out that the NFI index is sensitive to sample size and therefore suggested relaxing the standard to greater than .8. The NFI does not reflect model parsimony, which is why researchers often prefer the NNFI (TLI) index. The NNFI (TLI) value of this scale is .93, exceeding the .90 cutoff, thus meeting the fit standard. Overall, the scale's indicators show good overall model fit. Figure 4 presents the model structure and standardized parameter estimates from the confirmatory factor analysis.

Figure 4
Model Structure and Standardized Parameter Estimates from the Confirmatory Factor Analysis



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In terms of overall model reliability and validity, Squared Multiple Correlations (SMC) values ranged from .30 to .64, indicating a certain degree of individual reliability. Composite Reliability (CR) values ranged from .73 to .86, representing good reliability of the measurement indicators (Hair et al., 1998). Regarding validity, the Average Variance Extracted (AVE) values for the latent variables ranged from .46 to .57, indicating good convergent validity of the scale.

Overall, based on the evaluation results, the self-determination motivation scale, as extracted through exploratory factor analysis, has good model fit, CR, and convergent validity. Generally, the model's internal and external quality is good, making it suitable for studies on self-determination motivation in teaching integrated with information technology.

Changes in Weather Test

The Changes in Weather Test selected 58 multiple-choice questions from the curriculum question bank for a preliminary test with a class of 25 sixth-grade students. After the test, difficulty and discrimination indices were calculated. According to Henning's (1987) standards, questions with difficulty levels between .34 and .66 were selected. Based on Ebel's (1991) standards, questions with discrimination indices above .40 were retained, leaving 22 questions. Cronbach's α analysis was then performed, and $\alpha = .82$ indicated good internal consistency, demonstrating that the finalized test had strong reliability. The validity of the test was assessed using criterion-related validity, with the same class's fifth-grade second semester natural science final grades serving as the criterion. This yielded a Pearson correlation coefficient of $r = .64$, with $p < .001$. According to Cohen's (1988) standards, a correlation coefficient between .5 and 1 indicates a strong correlation, suggesting that the formal test effectively predicted the natural science learning effectiveness of this class.

Blooket Attitude Questionnaire

In this study, the Blooket Attitude Questionnaire was developed to assess students' perceptions, motivation, and engagement related to the use of Blooket. The questionnaire consisted of 18 close-ended items measured on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), as well as two open-ended questions. The open-ended questions asked students to (1) describe any difficulties they encountered while using Blooket and (2) indicate their favorite game mode. The questionnaire was administered post-intervention to 52 participants in the experimental group.

Data Analysis

The data analysis employed both quantitative and qualitative approaches. Quantitative data from the pretest and posttest on self-determined motivation and learning effectiveness were analyzed using SPSS 17. Descriptive statistics (means and standard deviations) were calculated for each dimension of the Self-Determination Motivation Scale. Independent samples *t* tests were then conducted to compare the experimental and control groups, with reverse scoring applied to negatively worded motivation items (e.g., Amotivation: Test Anxiety) to ensure consistency. Additionally, ANCOVA was conducted using pretest scores as covariates to isolate the effects of the intervention.

For the Changes in Weather Test, independent samples *t* tests were also conducted to assess differences in learning effectiveness before and after the intervention. These statistical methods provided a robust quantitative evaluation of the impact of formative assessment on learning outcomes.

Qualitative data from the Blooket Attitude Questionnaire were analyzed using thematic analysis to identify key themes related to usability, enjoyment, and learning motivation. Descriptive statistics, specifically mean scores and standard deviations for the Likert scale items, were calculated to provide a quantitative summary of participants' responses.

Research Results

Self-Determination Motivation Scale

As the number of items varied across sub-scales of the Self-Determination Motivation Scale, independent samples *t* tests were conducted using the average scores of each subscale and the overall scale. Amotivation: Test

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Anxiety, one of the dimensions, was reverse scored. Descriptive statistics for each dimension in the pretest and posttest are presented in Tables 2 and 3.

Table 2
Descriptive Statistics for Pretest Dimensions

Dimension name	Group	*M*	*SD*	Dimension name	Group	*M*	*SD*
SE	E	2.84	0.80	IRSD	E	2.81	1.07
	C	3.21	0.79		C	3.14	1.06
IR	E	3.69	0.80	ATA	E	2.55	1.13
	C	3.84	0.84		C	3.05	1.10
ER	E	3.03	1.00	TOTAL	E	3.06	0.55
	C	3.21	0.90		C	3.33	0.45
IREE	E	2.88	1.10				
	C	3.02	1.12				

Note. E = experimental group; C = control group

From Table 2, it can be seen that the average scores for the pretest dimensions of the experimental group are generally lower than those of the control group. Further analysis using an independent samples *t* test revealed significant differences in SE ($p = .021$, $d = 0.47$), ATA ($p = .024$, $d = 0.45$), and the total scale ($p = .006$, $d = 0.54$), indicating small to moderate effects favoring the control group. This suggests that, in the pretest, the experimental group had lower self-efficacy and higher test anxiety. Overall, the self-determination motivation of the experimental group was lower than that of the control group.

As shown in Table 3, the experimental group had higher average posttest scores than the control group. The independent samples *t* tests indicated significant differences in SE ($p < .001$, $d = 1.06$), IR ($p < .001$, $d = 1.20$), ER ($p < .001$, $d = 0.96$), ATA ($p < .001$, $d = 0.91$), and the total scale ($p < .001$, $d = 1.38$), all with large effect sizes. This indicates a substantial positive impact of the intervention on students' self-determined motivation. No significant differences were found in IREE ($p = .08$, $d = 0.34$) and IRSD ($p = .37$, $d = 0.17$).

Table 3
Descriptive Statistics for Posttest Dimensions

Dimension name	Group	*M*	*SD*	Dimension name	Group	*M*	*SD*
SE	E	3.87	0.80	IRSD	E	3.26	0.79
	C	3.05	0.75		C	3.41	0.94
IR	E	4.47	0.61	ATA	E	3.75	1.26
	C	3.60	0.82		C	2.74	0.95
ER	E	4.05	1.03	TOTAL	E	3.92	0.55
	C	3.08	1.00		C	3.20	0.49
IREE	E	3.45	1.17				
	C	3.08	0.97				

Note. E = experimental group; C = control group

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Changes in Weather Test

An independent samples *t* test was conducted to analyze the pretest and posttest results of the effectiveness test. The results are shown in Table 4.

Table 4
Independent Samples t Test Results for Pretest and Posttest on Learning Effectiveness

	M	*SD*	Levene's test		Equal means t test	
			F	*p*	*t*	*p*
Pretest						
E	15.67	5.80	1.14	.289	-3.71	< .001
C	19.67	5.17				
Posttest						
E	24.92	2.69	3.92	.050	0.94	.35
C	24.33	3.72				

Note. E = experimental group; C = control group; *df* = 102; $p < .05$

As shown in Table 4, the control group ($M = 19.67$) significantly outperformed the experimental group ($M = 15.67$) in the pretest ($p < .001$, $d = 0.73$). However, no significant difference was found in posttest scores ($p = .35$, $d = 0.18$), suggesting that the experimental group caught up following the intervention. ANCOVA revealed a significant difference in adjusted posttest scores ($p = .009$, $d = 0.51$), with the experimental group ($M = 25.45$) outperforming the control group ($M = 23.81$), indicating the effectiveness of using Blooket as a teaching approach.

Experimental Group's Blooket Attitude Questionnaire

Table 5 presents descriptive statistics for the close-ended items of the Blooket Attitude Questionnaire measured on a 5-point Likert scale.

Table 5
Descriptive Statistics for the Blooket Attitude Questionnaire

Questionnaire items	*M*	*SD*
1. I look forward to playing Blooket.	4.81	0.49
2. I find Blooket fun.	4.85	0.46
3. Blooket increases my interest in the course.	4.71	0.61
4. I am focused on every question in Blooket.	4.73	0.53
5. I try to answer every question in Blooket correctly.	4.65	0.62
6. I answer each question in Blooket as quickly as possible.	4.65	0.65
7. Competing with classmates in Blooket increases my learning motivation.	4.50	0.75
8. I really want to earn rewards in Blooket.	4.56	0.75
9. Because I want to win in Blooket, I pay more attention in class.	4.37	0.84
10. I enjoy learning through Blooket.	4.63	0.66
11. Blooket helps me learn the course content and remember it longer.	4.54	0.67
12. Blooket lets me know immediately what I don't know.	4.63	0.63

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Questionnaire items	*M*	*SD*
13. I am attracted to Blooket's game interface.	4.44	0.94
14. Blooket is easy to operate.	4.54	0.78
15. I hope other subjects could also use Blooket.	4.65	0.81
16. Blooket makes the classroom atmosphere more relaxed.	4.77	0.70
17. Blooket makes me more actively participate in classroom activities.	4.60	0.72
18. Blooket enhances my enthusiasm for class discussions.	4.21	1.14

Table 5 shows that students had a positive attitude toward Blooket, with all item means exceeding 4 on a 5-point Likert scale. Students reported that Blooket increased their interest in learning, enhanced their motivation, and improved the classroom atmosphere. They also found Blooket enjoyable and easy to operate, and many expressed interest in integrating Blooket into other subjects.

In terms of qualitative responses to two open-ended questions, most students did not report any difficulties. A small number mentioned issues such as unstable internet connections (2 students), tablet crashes (1 student), misunderstanding of game rules (2 students), or playing time being too short (1 student); 46 students did not respond. These challenges were primarily related to hardware or unfamiliarity with the interface and were typically resolved through peer support.

Regarding the second open-ended question, the most frequently selected modes were Crypto Hack (10 students), Tower Defense (8 students), and Gold Quest (7 students). Students cited enjoyment, fun, competition, and game mechanics—such as stealing coins—as the main reasons for their preferences.

Discussion

Prior research has indicated that as grade levels increase, learning motivation tends to decline, a trend exacerbated by students' shorter attention spans and preference for fast-paced, visually engaging content (Eccles et al., 1993; Prensky, 2001). To address these challenges, the present study integrated Blooket—a GIRS—into a sixth-grade natural science curriculum and examined its impact on student motivation and learning effectiveness. Although the experimental group initially performed lower than the control group in both learning outcomes and self-determined motivation, post-intervention assessments showed that they often caught up with or even outperformed the control group. These findings contribute to the existing literature by demonstrating that the integration of GIRS tools such as Blooket can effectively mitigate the motivational decline observed in upper primary school students.

In the pretest phase, the experimental group exhibited significantly lower self-efficacy and higher test anxiety, with moderate effect sizes favoring the control group. However, the posttest analysis revealed substantial improvements across most motivation subscales, with statistically significant gains in SE, IR, ER, and ATA, all showing large effect sizes. This suggests a strong positive impact of Blooket-integrated teaching on students' self-determined motivation. Although no significant differences were found in IREE and IRSD, the small effect sizes suggest more limited short-term gains in these areas. Despite having clearly instructed students to respond honestly and assured them that their answers would not affect the teacher's perception, the use of self-report instruments may still be subject to social desirability bias. Future studies are encouraged to complement self-reported data with behavioral or observational measures to obtain a more comprehensive understanding of student motivation.

Regarding learning effectiveness, the control group initially outperformed the experimental group in the pretest with a large effect size. However, no significant difference emerged in the posttest (small effect size), indicating that the experimental group closed the performance gap following the intervention. Notably, ANCOVA revealed a significant difference in adjusted posttest scores favoring the experimental group, with a moderate effect size, thus supporting the effectiveness of Blooket-integrated teaching.

Student responses to the Blooket Attitude Questionnaire further supported the intervention's impact. Quantitative results showed that all mean item scores exceeded 4 on a 5-point Likert scale, reflecting generally positive perceptions. Students reported that Blooket increased their learning interest, enhanced participation motivation, and improved the classroom atmosphere. Many expressed interest in using Blooket in other subjects. Qualitative responses echoed these themes, with students frequently citing excitement, enjoyment, and the motivational nature

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of competition as key reasons for their engagement. Technical issues such as internet instability or unfamiliarity with game rules were minimal and typically resolved with peer assistance.

These findings align with claims that digital-native learners are particularly responsive to interactive, game-based learning environments that provide immediate feedback and visual stimulation (Prensky, 2001). The observed motivational gains are also consistent with SDT (Deci & Ryan, 1985), which posits that environments fostering autonomy, competence, and relatedness enhance intrinsic motivation. The lack of significant differences in IREE and IRSD may reflect the deeper psychological nature of these constructs, which are less responsive to short-term interventions and may require sustained or individualized support (Koestner & Losier, 2004).

Taken together, these findings demonstrate that incorporating GIRS platforms like Blooket into primary science education can enhance learning motivation, engagement, and performance. Such tools show strong potential for addressing the evolving needs of today's learners in digitally enriched classrooms. Nevertheless, the use of convenience sampling from a single school may limit the generalizability of the findings. Future research should consider employing stratified or randomized sampling across diverse school contexts to enhance external validity.

Conclusions and Implications

From a theoretical standpoint, this study supports the applicability of SDT in technology-enhanced learning contexts. The findings underscore the importance of aligning digital teaching tools with motivational frameworks to foster more effective and engaging learning environments. Despite the observed benefits, several implementation challenges emerged. First, technical difficulties required teachers to not only possess basic troubleshooting skills but also demonstrate a willingness to adopt online IRSs. Second, the system's limited question formats—confined to multiple-choice and fill-in-the-blank—may encourage guessing and reduce cognitive engagement. Third, logistical concerns, such as device distribution and game setup, consumed valuable teaching time. These factors highlight the need for careful planning when integrating such tools into classroom practice.

To address these issues, it is recommended that schools invest in more robust network infrastructure and provide ongoing professional development in educational technology. Developers should consider adding features that reduce random guessing and enhance question diversity. Additionally, teachers may benefit from leveraging digitally skilled students to assist peers with connectivity, operation, and device management.

Future studies should examine the sustained effects of various online IRSs across subjects and grade levels to better understand their long-term educational value. Such investigations can inform the development of scalable, theory-driven digital interventions that support both motivation and learning outcomes in contemporary classrooms.

Declaration of Interest

The author declares no conflict of interest.

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THE EFFECTS OF SCIENCE CLUB ACTIVITIES ON SECONDARY SCHOOL STUDENTS' CREATIVE SELF-EFFICACY: MEDIATING QUALITY EDUCATION AND MODERATING ICT USAGE

Weimiao Wu,
Kyung Hee Park

Abstract. *Engagement in science club activities at school has been identified as a crucial experience for developing creative self-efficacy while also fostering students' social and emotional growth. The effects of science club activities on students' creative self-efficacy were analyzed using difference verification and structural equation modeling in this study, focusing on a sample of 5,737 Korean secondary school students. Additionally, the study explored the mediating effects of quality teacher and classroom support, which can enhance academic achievement, while concurrently assessing the experience of ICT usage at school. The analysis results indicated that all proposed hypotheses were statistically significant, particularly confirming that secondary school students with internet usage experience exhibit higher levels of creative self-efficacy in science club activities. Finally, this study demonstrated the conflicting moderating effects of computer and smartphone use on the association between science club activities and creative self-efficacy. Therefore, the study emphasized the importance of science club activities supported by quality emotional support from teachers and the implementation of teaching and learning strategies that systematically manage ICT use among secondary school students.*

Keywords: *science club activity, creative self-efficacy, quality education, ICT usage, secondary school student*

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Introduction

As technology and society continue to evolve rapidly, education must extend beyond focusing solely on academic achievement. Today's students need to develop essential 21st-century competencies, commonly summarized as the "4Cs", which include creativity, critical thinking, communication, and collaboration (Michael & Miranda, 2024). These competencies are essential for helping students face a digital and connected world. Beghetto (2006) and Farmer and Tierney (2017) have stressed the importance of designing school curricula that support creativity and convergent thinking. However, even though many educators agree on the importance of the 4Cs, these competencies are often treated as secondary or optional. In many classrooms, lecture-based, teacher-centered teaching methods still dominate, making it difficult to use more active and student-centered approaches that could better support the development of these important competencies.

In particular, since college advancement is central to educational policy in South Korea, the shift toward enhancing cognitive academic achievement in reading, writing, and arithmetic (3Rs) through teacher-centered education is progressing slowly. To address this educational challenge, the Korean Ministry of Education has expanded and supported creative experiential activities and club activities as part of its innovative education policy (Jung et al., 2015). Although the proportion of scheduled time allocated to these activities is not substantial, they promote the development of creativity and social skills through student-led academic experiences in areas such as science, computers, and citizenship (Kim & Kim, 2014). For instance, science club activities are conducted in various ways, including chemistry and physics experiments, robotics, environmental science exploration, participation in science and engineering competitions, and digital projects (Kwon et al, 2024). Similarly, France's "Science at School" policy is a nationwide program characterized by a cycle-based system that spans from kindergarten through secondary education (Carvalho et al., 2019). It particularly emphasizes the Fab Labs (Fabrication Laboratories) approach, which enables students to engage

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in hands-on scientific experiences. Both South Korea and France share the common goal of encouraging students to experience science in a self-directed manner. However, while France provides continuous scientific experiences aligned with students' developmental stages, South Korea's science education is not systematically connected across different school levels. Through direct experience, students undergo personal growth and improve academic achievement (Lipscomb, 2007; Song et al., 2012; Williams & Gottfried, 2010). Eccles and Barber (1999) have found that students who engaged in school-based academic clubs achieved high school GPA outcomes that exceeded expectations. Therefore, it is essential to assess the effectiveness of these accumulated science club activities in fostering creative competencies to derive significant educational outcomes from these policies.

In an effort to improve learning outcomes, the international community has promoted an agenda called "quality education" under Sustainable Development Goal 4 (SDG4) since 2015. At this point, quality education encompasses the ability to achieve meaningful and effective learning outcomes (SDG 4.1) and emphasizes the professionalism and teaching-learning efforts of teachers (UN, 2015). In order to realize such quality education, teachers should provide learning opportunities and sufficient time to facilitate the implementation of personalized instruction for students (Osakwe, 2014). Furthermore, beyond traditional lecture-based teaching, teachers should continuously design and apply a variety of instructional activities to meet diverse learning needs (Krulj et al., 2024). Since the late 20th century, many countries have invested in information and communication technology (ICT) infrastructure within schools; however, such efforts have predominantly focused on the instructional applications of ICT by teachers. When ICT—recognized as a fundamental public good—is integrated into school settings in ways that mirror its everyday use in broader society, schooling can more effectively cultivate competencies that are closely linked to students' real-life experiences. Nevertheless, many schools worldwide tend to restrict students' Internet usage during school hours. However, this controlling trend requires improvement (UNESCO, 2023). It is essential to develop teaching and learning methods that transform these ICT activities into effective learning experiences, rather than merely restricting them from a control standpoint (Schaumburg, 2018).

Therefore, this study aimed to explore the effects of science club activities on creative self-efficacy, focusing on the mediating roles of quality education—specifically, quality teacher support and quality class support. Furthermore, from the perspective of creativity as the ability to explore and reconstruct information, this study examined how students' ICT-related experiences at school moderate this process. The results of this study are anticipated to offer valuable insights into the educational strategies that schools should adopt, both quantitatively and qualitatively, to foster the essential competencies required for students in the digital revolution era.

Literature Review

Science Club Activities at School

To cultivate scientifically literate citizens for the future, science education serves as a crucial educational tool that equips students to examine natural phenomena and address scientific challenges, thereby fostering creative problem-solving and integrative thinking. Currently, there has been a widespread lack of interest in the natural sciences among young people, as has been evidenced by international assessments (Krapp & Prenzel, 2011; Sahin, 2013). For instance, international assessments such as TIMSS and PISA have indicated that U.S. students are underperforming in mathematics and science, which threatens the United States' global leadership (Schmidt, 2011). A similar trend has been observed in South Korea, where student performance in science has consistently declined in recent years, as reported by the Organization for Economic Co-operation and Development (OECD, 2007).

To stimulate and sustain interest and curiosity in science, Hartley (2014) has emphasized the importance of adopting appropriate tools and engagement methods to involve young students in scientific exploration. Recent studies have confirmed that engagement in science club activities significantly enhances students' interest in science (Jung et al., 2015; Kim & Kim, 2014; Song & Lee, 2013). A science club is a gathering of individuals with shared interests, whether in school or the broader community, aimed at exchanging hobbies, skills, and values. Participation in such clubs has been shown to effectively improve students' adjustment to school and foster the development of their personality and emotional characteristics (Hur & Kang, 2010; Song et al., 2012).

While there is limited research assessing the association between field-specific extracurricular clubs and the effects of science education, the significance of student participation in these clubs has been widely recognized worldwide. Williams and Gottfried (2010) have confirmed that informal STEM exposure, both in-school and out-of-school, is critical to students' trajectories into (or out of) STEM-related careers. Additionally, according to Eccles and Barber (1999), school-based academic club involvement positively correlated with improved high school GPAs.

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In examining how extracurricular club involvement influences STEM achievement, Lipscomb (2007) reported that participation in extracurricular clubs improved 2% and 1% gains in math and science test scores, respectively, among middle school students. It is evident that science club activities not only provide students with opportunities for hands-on and experimental research but also stimulate interest in science and foster the development of creative thinking. These activities have had a profound effect on students' personal growth, academic development, and future career choices (Kim & Kim, 2014; Lipscomb, 2007). Overall, science clubs serve as a vital educational resource globally, particularly in enhancing students' creative self-efficacy and promoting scientific literacy.

Creative Self-Efficacy Among Students

In this era of rapid change, the OECD (2014) identifies creativity as a critical competency that youth need to master in the 21st century. As the importance of innovation has grown, extensive research has explored the factors influencing innovativeness, with creativity self-efficacy being recognized as a crucial predictor of creative achievement and performance (Karwowski, 2011; Karwowski & Lebuda, 2016; Tierney & Farmer, 2002). Defined as individuals' belief in their capacity to generate creative outcomes (Tierney & Farmer, 2002), creative self-efficacy extends Bandura's (1997) broader concept of self-efficacy to the domain of creativity.

Creative self-efficacy is particularly important in educational settings because it influences students' motivation to participate in activities that foster creative thinking and problem-solving abilities. In particular, secondary school students (ages 12-18) represent a critical period for the development of self-efficacy, as their self-efficacy can significantly affect their academic performance, participation in extracurricular activities, and overall learning outcomes. For instance, Beghetto's (2006) study of secondary school students demonstrated that students with high creative self-efficacy tend to perceive academic success more positively and have greater motivation to learn. Furthermore, these students have shown greater engagement in extracurricular activities. Furthermore, Farmer and Tierney (2017) have emphasized that creative self-efficacy is a crucial motivational driver in education. Their cross-level study indicated that students who have strong creative self-efficacy are more likely to set and pursue challenging creative goals, engage persistently in problem-solving tasks, and maintain a positive outlook toward innovation. This underscored the central role of creative self-efficacy in fostering student motivation and engagement in learning.

Engagement in scientific learning and related activities serves a pivotal function in cultivating students' creative self-efficacy. Scientific learning often requires students to formulate hypotheses, design experiments, and develop innovative solutions to complex problems (Jung et al., 2015). These processes offer valuable opportunities for students to test their ideas, reflect on failures, and build confidence in their creative abilities. Such experiences enable students to overcome challenges and foster both creative thinking skills and a strong belief in their own creative potential. Research has shown that science learning environments promoting autonomy, problem-solving, and open-ended inquiry can significantly enhance students' creative self-efficacy (Beghetto, 2006; Tierney & Farmer, 2002). Currently, research on creative self-efficacy has primarily concentrated on the association between efficacy beliefs and creative outcomes. However, few studies have examined the predictors that influence creativity self-efficacy and the role of the school environment in this regard.

Quality Education in the Classroom

The United Nations Sustainable Development Goal 4 (UN-SDG4) emphasized the necessity of providing all students with equitable access to quality education, which is essential for achieving meaningful and effective learning outcomes (UN, 2015). In contemporary educational research, the concept of quality education is closely linked to the transfer of academic knowledge and the cultivation of learner competencies. To achieve these goals, dual support from teachers and the classroom environment is essential. Schools that provide such support are more likely to engage students, strengthen their connection to school, and promote effective learning outcomes (Klem & Connell, 2004).

Quality teacher support refers to the effective assistance and guidance provided by educators during teaching and learning activities. This support primarily encompasses both emotional and academic support for students (Birch & Ladd, 1997; Furrer & Skinner, 2003). Research has confirmed that teacher support fosters more positive teacher-student relationships and motivates students to engage in classroom activities (Ryan & Patrick, 2001), as well as to invest more energy in academic tasks (Boulton et al., 2012). Furthermore, teacher support plays a critical role in students' academic outcomes while also enhancing their academic mood. A meta-analysis has demonstrated

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that teacher support is positively correlated with students' academic mood (Lei et al., 2018). Specifically, teacher support and encouragement can significantly enhance students' motivation and self-confidence in their learning (Hughes & Chen, 2011). Recent studies have also focused on how teacher support influences the creative self-efficacy of middle school students (Liu et al., 2021). It is believed that students who perceive a higher degree of teacher support exhibit greater autonomous motivation, which in turn contributes to increased creative self-efficacy.

Achieving quality education requires not only the support of teachers but also a quality class environment. Researchers and experts define quality education as authentic education that emphasizes the development of students' creativity, critical thinking, self-confidence, and other lifelong learning skills. Therefore, it is essential to support authentic education by promoting an effective classroom learning environment (Osakwe, 2014). Specifically, quality classroom support includes a range of elements such as learning resources, teaching methods, and classroom management. In particular, science club activities often adopt a hands-on and inquiry-based instructional approach, which requires a classroom environment that not only provides the necessary learning resources but also stimulates students' desire to explore. Numerous studies have demonstrated that support from the external environment plays a crucial role in stimulating students' intrinsic motivation (Krulj et al., 2024; Wu, 2003), and students' perceived classroom support has been identified as a vital component of the school environment. For instance, with the advancement of technology, research has shown that integrating emerging technologies into traditional classrooms to create smart learning environments can significantly increase student engagement and, consequently, maximize student potential (Wang et al., 2022).

Therefore, high-quality teacher support can help students maintain confidence when facing challenges and foster creative thinking through positive feedback. In turn, effective classroom support creates an open and resourceful environment that stimulates students' creative potential.

ICT-Usage at Schools

With the growing integration of information technology into the education sector, the integration of information and communication technology (ICT) in schools has emerged as a key driver of educational development. ICT has transformed teaching methodologies and significantly shaped students' learning experiences (Amutha, 2020). Research has indicated that the application of ICT in schools has a significantly positive effect on students' scientific literacy (Guo et al., 2022). Another study has shown that schools equipped with advanced ICT facilities enable students to more easily access scientific knowledge, conduct simulated scientific experiments, and engage in external academic interactions (Korukluğlu & Yucel-Toy, 2022). Such accessibility has not only improved learning efficiency but also stimulated students' interest and creativity in the learning process (Schaumburg, 2018).

With this trend, many governments worldwide have introduced policies to strengthen ICT infrastructure in educational institutions. For example, countries such as South Korea and Singapore have achieved levels of ICT integration in education comparable to those of the United Kingdom and the United States (Farrell & Wachholz, 2003). In recent years, developing countries have also increased their investments in educational ICT (Farrell & Wachholz, 2003). However, it is important to note that this advancement does not diminish the role of teachers. On the contrary, collaborative support among teachers and schools serves as a critical factor in realizing the full potential of ICT to facilitate student learning (Schaumburg, 2018).

ICT primarily encompasses various forms such as computers, internet access, and smartphones. The use of different types of ICT tends to yield varying effects on learning outcomes (Kates et al., 2018; Schaumburg, 2018). In classroom instruction, computers are generally categorized into two types of applications: information tools and learning tools. On one hand, students can use computers to search for information and enhance their fundamental academic skills; on the other hand, they can engage in scientific inquiry and participate in simulation-based experiments (Tondeur et al., 2007).

Furthermore, incorporating internet access into classroom teaching has been shown to support teachers in presenting instructional content more effectively, accelerating the pace of instruction, and increasing student engagement (Korukluğlu & Yucel-Toy, 2022; Schaumburg, 2018). However, these positive outcomes largely depend on teachers' levels of computer proficiency and their attitudes toward technology use in education (Julia & Dagmar, 2024; Tondeur et al., 2007).

Regarding the use of smartphones, students can utilize them to document key aspects of the learning process and share content through social or collaborative platforms, thereby enhancing peer interaction and discussion (Ilomäki, 2008; Zheng et al., 2021). Nevertheless, empirical studies have shown that the impact of smartphone use on positive learning outcomes is relatively limited (Frohberg et al., 2009; Hawiet & Samaha, 2016). Moreover, some

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researchers have expressed concerns that inappropriate or excessive use may lead to distraction and negatively affect students' academic performance (Gi et al., 2016).

Associations Between the Variables

Science club activities have been demonstrated to enhance students' interest in science and boost their academic motivation and confidence through practical, inquiry-based experiences (Hong et al., 2013; Jung et al., 2015). Such activities provide opportunities for creative expression and may serve as a foundation for the development of creative self-efficacy (Tierney & Farmer, 2002). However, achieving these benefits requires the reinforcement of high-quality education, in which teachers play an indispensable role.

In particular, quality education—including teacher support and a positive classroom environment—may mediate the association between participation in science club activities and creative self-efficacy. Based on Self-Determination Theory, environments that promote autonomy and provide constructive feedback foster students' intrinsic motivation, which is closely linked to creativity (Deci & Ryan, 2000). Empirical studies have demonstrated that teacher support and classroom dynamics significantly enhance students' creative self-efficacy (Beghetto, 2006; Puozzo & Audrin, 2021). Consequently, the mediating model proposed in this study is illustrated in Figure 1.

Moreover, the ICT environment in schools, as a critical component of the learning context, may influence the effect of science club activities on students' creative self-efficacy. Specifically, during science club activities, students may use computers for data analysis and experimental simulations; access the internet to consult the latest scientific findings and participate in online academic discussions; and utilize smartphones to conduct field investigations and record observations, thereby promoting peer communication and interaction (Korukluoğlu & Yucel-Toy, 2022). Accordingly, this study constructed a moderated mediation model to examine how three specific dimensions of ICT usage in schools—computer use, internet access, and smartphone usage—moderate the associations within the model (shown in Figure 2).

Understanding these associations, this study provided insights into how science club activities contribute to creative self-efficacy among Korean secondary school students. Specifically, it examined whether quality education—represented by teacher support and classroom environment—mediates this correlation, and whether students' ICT usage at school moderates this effect.

This study posed the following three research questions:

Are science club activities effective in enhancing creative self-efficacy in secondary school students?

Does quality education mediate the association between science club activities and creative self-efficacy?

Does ICT usage at school (computer, internet access, smartphone) moderate the mediating effect of quality education?

Figure 1
Partial Mediating Model

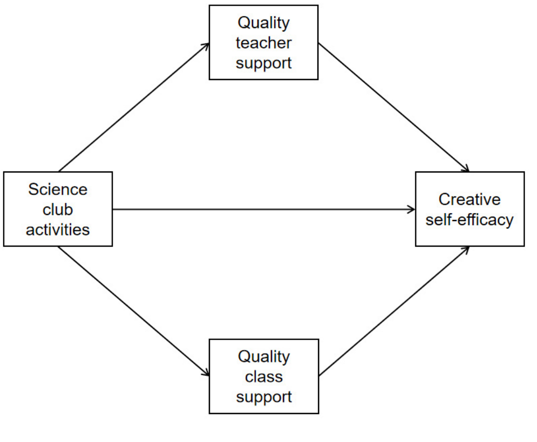
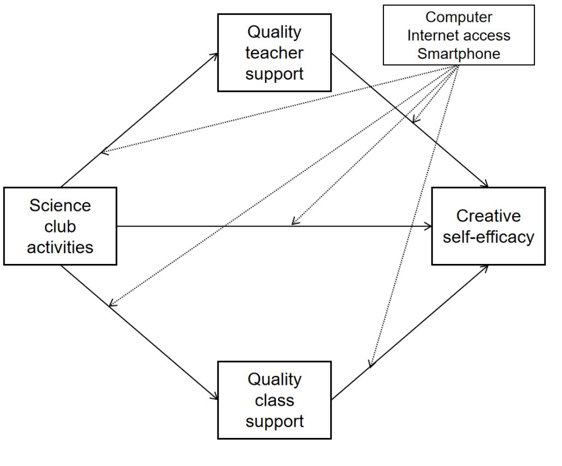


Figure 2
Moderating Model by Multi-group



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Research Methodology

Design

A quantitative research design was adopted in this study, drawing on data from the 2022 Program for International Student Assessment (PISA 2022). It focused on analyzing the potential correlations between participation in science club activities, quality education, and creative self-efficacy among secondary school students in South Korea. The research specifically targets 16-year-old secondary school students who participated in the PISA assessment, providing a nationally representative dataset of their educational experiences and competencies. The data were analyzed using structural equation modeling (SEM).

Participants

The analysis was based on the PISA 2022 survey data for South Korean secondary school students. The OECD has conducted the PISA assessment every three years, aiming to evaluate the abilities and competencies of students worldwide in preparing for future life challenges. The 2022 PISA assessment involved around 690,000 students across 81 countries and economies. The students in this study were between 16 and 17 years old and had completed at least six years of formal education at the time of testing. The data included a sample of students from various academic ability levels, ensuring the representativeness and diversity of the sample.

A total of 6,454 South Korean student samples participated in this study, and after excluding 717 incomplete samples, 5,737 valid responses were included in the analysis. The gender distribution was nearly equal, comprising 2,922 male students (50.9%) and 2,815 female students (49.1%). In terms of age, the majority of the sample consisted of 16-year-old students (5,400, or 94.1%), while 337 students were aged 17 (5.9%). Additionally, the study examined the distribution of students' ICT usage at school. A total of 3,720 students (64.8%) reported having used computer at school, while 2,017 students (35.2%) did not; 3,752 students (65.4%) reported that their school was accessed internet, while 1,985 students (34.6%) did not; 4,899 students (85.4%) reported having used a smartphone at school, while 838 students (14.6%) did not. Table 1 provides an overview of the participants' demographic characteristics.

Table 1
Demographics of Participants

Variables		Items	*N*	%
Gender		Male	2,922	50.9
		Female	2,815	49.1
Age		16	5,400	94.1
		17	337	5.9
ICT usage at school	Computer	Inexperienced	3,720	64.8
		Experienced	2,017	35.2
	Internet access	Inexperienced	3,752	65.4
		Experienced	1,985	34.6
	Smartphone	Inexperienced	4,899	85.4
		Experienced	838	14.6
Total			5,737	100.0

Measurements

To validate the research model, the following construct variables were evaluated using the PISA questionnaire. First, participation in science club activities at school was assessed using the question, "In your school, how often do you participate in science club activities?" The responses for this question used a Likert scale ranging from 'Never'

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to 'Every Day,' with an additional option of 'Not Available at School.' The scale was scored on a 6-point scale, where a higher score indicated a greater level of participation in science club activities.

Next, quality teacher support refers to the effective assistance and guidance provided by educators during educational activities. It was assessed using the question, "Do you agree that my teachers allow me sufficient time to develop creative solutions to assignments?" A Likert scale was used for this item, ranging from 'Strongly Disagree' to 'Strongly Agree,' with higher values signifying stronger positive perceptions of teacher support. For quality class support, this study utilized the question, "Do you agree that the activities we engage in during my classes help you think of new ways to solve problems?" This was also assessed using a Likert scale, where higher scores indicated stronger agreement with the statement.

Additionally, to measure the frequency of students' ICT usage at school, three items were employed: computer, Internet access, and smartphone. Students were asked how often they used (1) desktop or laptop computers, (2) Internet access (excluding smartphones), and (3) smartphones (i.e., mobile phones with Internet access) at school. Participants responded using a 5-point Likert scale, with options ranging from 'Never' to 'Several times a day'. Higher scores indicated more frequent use of each ICT tool during school hours.

Finally, students rated their confidence in performing a variety of tasks that reflect creative skills. For instance, two of the items included "How confident are you about coming up with creative ideas for school projects?" and "How confident are you about thinking of many good ideas for science experiments?" Each of the eight items in this scale provided four response options: 'Not at all confident' to 'Extremely confident.' Creative self-efficacy demonstrated acceptable internal consistency, as evidenced by a Cronbach's alpha of .966.

Data Analysis

Multiple statistical analyses were conducted to assess the quality and reliability of the collected data. The data analysis process began with descriptive statistics to understand the basic characteristics of the sample, including the mean, standard deviation, and range of each variable. Next, to further examine the effect of ICT usage (computers, internet access, and smartphones) experience on students' participation in science club activities and their creative self-efficacy, an independent samples t-test was conducted. The sample was divided into two groups based on whether students had ICT usage experience at school. This test allowed for the assessment of whether ICT usage experience significantly influenced these variables. After conducting preliminary analyses using descriptive statistics and the t-test, the study constructed a Structural Equation Model (SEM) to validate the mediating role of quality education between participation in science club activities and creative self-efficacy. To ensure the model's applicability, AMOS 26.0 software was utilized for model fitting, and the model was evaluated based on fit indices such as the Comparative Fit Index (CFI) and the Tucker-Lewis Index (TLI). Finally, considering that ICT usage may have a moderating effect across different student groups, a Multi-Group Analysis was performed to examine how ICT usage moderated the aforementioned pathways.

Research Results

Differences in ICT Usage at School

To understand the levels of students' engagement in science club activities, quality education, and creative self-efficacy, this study examined differences in the use of computers, internet access, and smartphones at school (see Table 2).

An independent samples t-test revealed statistically significant differences ($p < .001$) between students with and without computer usage experience in terms of science club activities ($t = 8.20$), quality teacher support ($t = 4.77$), quality class support ($t = 5.71$), and creative self-efficacy ($t = 6.67$). Students with and without internet access experience at school showed significant differences ($p < .001$) in science club activity ($t = 9.43$), quality teacher support ($t = 4.83$), quality class support ($t = 5.90$), and creative self-efficacy ($t = 7.33$). These results indicated that students with relevant experience outperformed those without computer and internet access at school in science club activities, quality teacher support, quality class support, and creative self-efficacy. Additionally, there were significant differences ($p < .01$) between students with and without smartphone usage experience in terms of creative self-efficacy ($t = 3.06$). The findings confirmed that students with smartphone usage experience at school had higher levels of creative self-efficacy.

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Table 2
Comparing the Differences in ICT Usage at School

Construct		Science club activities		Quality teacher support		Quality class support		Creative self-efficacy	
		***M* (*SD*)**	***t***	***M* (*SD*)**	***t***	***M* (*SD*)**	***t***	***M* (*SD*)**	***t***
Total		2.12 (1.47)	–	2.78 (0.67)	–	2.77 (0.70)	–	2.61 (0.73)	–
Computer	Experienced	2.23 (1.50)	8.20***	2.82 (0.66)	4.77***	2.81 (0.69)	5.71***	2.66 (0.73)	6.67***
	Inexperienced	1.91 (1.40)		2.73 (0.68)		2.70 (0.71)		2.53 (0.74)	
Internet access	Experienced	2.25 (1.48)	9.43***	2.82 (0.65)	4.83***	2.81 (0.68)	5.90***	2.66 (0.72)	7.33***
	Inexperienced	1.87 (1.42)		2.72 (0.70)		2.69 (0.74)		2.51 (0.75)	
Smartphone	Experienced	2.13 (1.45)	1.43	2.79 (0.66)	1.69	2.78 (0.69)	1.57	2.63 (0.73)	3.06**
	Inexperienced	2.05 (1.57)		2.75 (0.70)		2.73 (0.75)		2.54 (0.77)	

Note. $^{**}p < .01$, $^{***}p < .001$

Verification of the Mediating Effect of Quality Education

To further analyze the associations among science club activities, quality education, and creative self-efficacy, a mediation effect test was conducted on the two dimensions of quality education (quality teacher support and quality class support). As shown in Table 3, the model fit values for the full sample were $\chi^2/df = 120.465$ ($p < .001$), with both the TLI and CFI exceeding 0.90, thereby meeting the acceptance criteria.

As shown in Table 4, all path results were statistically significant ($p < .001$), providing strong support for the correlations among the variables in the model. Specifically, the independent variable (science club activities) had a positive influence on both the dependent variable (creative self-efficacy) and the mediator variables (quality teacher support and quality class support) ($\beta = .060$, $p < .001$; $\beta = .047$, $p < .001$; $\beta = .059$, $p < .001$). In particular, the mediator variables (quality teacher support and quality class support) also positively influenced the dependent variable (creative self-efficacy) ($\beta = .167$, $p < .001$; $\beta = .157$, $p < .001$). These results suggest that as students perceive higher quality education, their creative self-efficacy is likewise enhanced. The final model's path coefficient results are illustrated in Figure 3.

Additionally, a bootstrapping method was employed to verify the mediation effect, with a sample size of 2,000. As shown in Table 5, both quality teacher support and quality class support had a significant effect on science club activities and creative self-efficacy, with indirect effect values of .008 and .009, respectively. The confidence intervals did not include zero, and the p-values were less than .001, thereby confirming their mediating roles. Consequently, these results emphasize that improving the quality of education is essential for promoting students' creative self-efficacy.

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Figure 3
Path Diagram and Standardized Estimate of Research Model

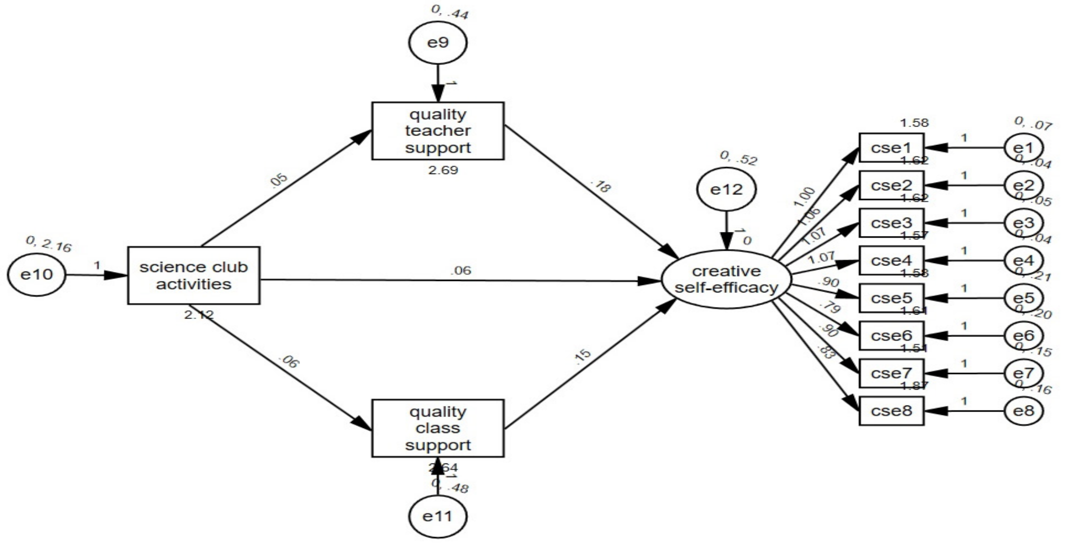

Table 3
Fit indices for the Research Model

Model	*df*	χ^2/df	*TLI*	*CFI*
Full sample	42	120.465***	.907	.929

Note. ****p* < .001

Table 4
Significance Verification for the Research Model

Path	β	*SE*	Bootstrap 2000 times 95% bias-corrected CI
Science club activities → Quality teacher support	.047***	.006	.035 ~ .058
Science club activities → Quality class support	.059***	.006	.047 ~ .072
Science club activities → Creative self-efficacy	.060***	.006	.048 ~ .072
Quality teacher support → Creative self-efficacy	.167***	.020	.128 ~ .206
Quality class support → Creative self-efficacy	.157***	.019	.119 ~ .194

Note. ****p* < .001

Table 5
Significance Verification of Mediating Effect

Path	β	*SE*	Bootstrap 2000 times 95% bias-corrected CI
Science club activities → Quality teacher support → Creative self-efficacy	.008***	.002	.005 ~ .011
Science club activities → Quality class support → Creative self-efficacy	.009***	.002	.006 ~ .013

Note. ****p* < .001

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Verification of Multi-group Comparison for ICT Usage

Finally, multi-group analyses were conducted to verify the moderating effects of computer use, internet access, and smartphone usage in schools. The results indicated that the model fit for the multi-group analysis met the established acceptance criteria, as shown in Table 6.

The findings indicated that science club activities in both groups, with and without computer usage at school, had a significant positive effect on quality education ($p < .001$), and quality education also had a significant positive effect on creative self-efficacy ($p < .001$). Since the differences in the paths from 'science club activities → quality class support' and 'quality teacher support → creative self-efficacy' between groups with and without computer usage experience were -2.154 and -2.802, respectively, all of which were greater than |1.96|, indicating that these path differences were statistically significant. Since the differences in all paths between groups with and without internet access at school did not meet the acceptance criteria, indicating that all path differences were not statistically significant.

Regarding smartphones, the findings revealed that science club activities in both groups—with and without smartphone usage at school—had a significant positive effect on quality education ($p < .001$). Additionally, quality education had a significant positive effect on creative self-efficacy ($p < .001$). The differences in the paths from 'quality teacher support → creative self-efficacy' and 'quality class support → creative self-efficacy' between groups with and without smartphone usage experience were 3.643 and -1.993, respectively. Both values exceed the critical value of |1.96|, indicating that these path differences were statistically significant. As a result, the moderating effect of smartphone use at school was confirmed, and the mediating effect of quality teacher support (β = .269) was found to be stronger in the group that did not use smartphones (see Table 7).

Table 6
Nested Multi-Group Model Fits

Structural residuals	*df*	χ^2/*df*	*TLI*	*CFI*
Computer	111	47.443***	.927	.926
Internet access	111	47.849***	.926	.926
Smartphone	111	46.519***	.929	.928

Note. ***$p < .001$

Table 7
Significance Verification of Multi-group Path Analysis

Path	Inexperienced		Experienced		Between groups
	β	*SE*	β	*SE*	
Path toward Computer					
Science club activities → Quality teacher support	.117***	.007	.057*	.011	-1.852
Science club activities → Quality class support	.142***	.007	.071**	.011	-2.154
Science club activities → Creative self-efficacy	.110***	.008	.093***	.012	-.293
Quality teacher support → Creative self-efficacy	.185***	.018	.109***	.025	-2.802
Quality class support → Creative self-efficacy	.141***	.017	.143***	.023	.019
Path toward Internet access					
Science club activities → Quality teacher support	.099***	.007	.088***	.011	.036
Science club activities → Quality class support	.131***	.007	.089***	.012	-.959
Science club activities → Creative self-efficacy	.100***	.008	.111***	.012	.721
Quality teacher support → Creative self-efficacy	.170***	.018	.133***	.024	-1.572
Quality class support → Creative self-efficacy	.136***	.017	.155***	.023	.414

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Path	Inexperienced		Experienced		Between groups
	β	*SE*	β	*SE*	
Path toward Smartphone					
Science club activities → Quality teacher support	.103***	.006	.095**	.015	-.290
Science club activities → Quality class support	.126***	.007	.117***	.016	-.216
Science club activities → Creative self-efficacy	.103***	.007	.152***	.017	-1.317
Quality teacher support → Creative self-efficacy	.139***	.016	.269***	.037	3.643
Quality class support → Creative self-efficacy	.153***	.015	.085**	.035	-1.993

Note. *$p < .05$, **$p < .01$, ***$p < .001$

Discussion

This study quantitatively analyzed the academic effects of science club activities on secondary school students, and the main results are as follows.

First and foremost, the research revealed that participation in science club activities significantly contributed to the enhancement of creative self-efficacy among secondary school students. This finding was consistent with previous studies, such as those by Hartley (2014), Kwon et al. (2024), and Song et al. (2012), which emphasized the importance of science club activities in fostering creative and transformative competencies. While the dependent variable of this study, creative self-efficacy, is characterized by non-cognitive traits rather than being directly measurable as creativity, it is important to note that the emotional attitudes associated with efficacy are linked to practical capabilities (Beghetto, 2006; Karwowski & Lebuda, 2016; Tierney & Farmer, 2002). In addition to enhancing creative competencies, the club-based science learning focused on in this study had various educational effects. Lipscomb (2007) demonstrated that interactive learning reinforces problem-solving skills and teamwork, while Kim and Kim (2014) highlighted the development of social skills through school club activities. Given that the convergent competencies, as the 4Cs required in the digital society, encompass not only creativity but also communication and collaboration, it is essential to actively promote student-led club activities in the future.

Moreover, this study confirmed that the quality of teaching and learning provided by teachers in the classroom further strengthened the causal association between science club activities and creative self-efficacy, serving as a mediating factor. When teachers allocated sufficient time for students to creatively develop solutions and engaged them in classroom activities that facilitated problem-solving, the creative self-efficacy of secondary school students was found to be significantly enhanced. This finding aligns with the suggestion by Dearden et al. (2002) that selective schools tend to achieve better educational outcomes. Dearden et al. (2002) indicated that when controlling for ability and family background, there was generally no significant association between educational quality and academic achievement. This observation is consistent with the educational equity theory of Coleman et al. (1966), who found that the effect of educational conditions was minimal. However, Gerick and Killus (2024), along with Dearden et al. (2002) and Rutter (1983), asserted that the educational effects of specialized classes and tailored support from teachers may vary, which aligns with the results of this research. In other words, offering advanced educational support, beyond the basic quality education (e.g., student-to-teacher ratio) provided to all students, results in positive learning outcomes. This argument regarding the importance of careful and emotional support from teachers has also been highlighted in studies by Hughes and Chen (2011), Lei et al. (2018), and Liu et al. (2021).

Next, concerning the variation in Internet usage among secondary schools across different countries, this study confirmed that students should develop tolerance towards Internet use in order to effectively engage with the digital society. Apart from the United States and Germany, most countries, including South Korea, restrict secondary school students from accessing the Internet during school hours. In contrast, this study revealed that secondary school students who experienced Internet use in schools were more active in science club activities and exhibited significantly higher levels of creative efficacy. The mean science club activity score for students with Internet experience at school was 2.25, while the score for students without Internet experience was 1.87, indicating a significant difference between the two groups. Additionally, the mean score for creative self-efficacy based on Internet use experience was 2.66 for those with experience and 2.51 for those without, also demonstrating a significant difference. Schaumburg (2018) and Tonderur et al. (2007) reported similar findings, confirming that Internet use experience in school enhances learning efficiency. This study confirmed that the educational effect

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of smartphone use is relatively minor compared to that of Internet use in schools. In particular, the difference in science club activities based on smartphone use was not significant (t = 1.43), which aligns with the finding of Kates et al. (2018). These research results suggest that positive learning effects may vary depending on the type of ICT employed.

Furthermore, this study empirically demonstrated the conflicting moderating effects of ICTs, such as computer and smartphone usage, on the association between science club activities and the creative self-efficacy of secondary school students. The findings indicated that for students with experience using computers in schools, the effect of high-quality teacher support on creative self-efficacy was notably more pronounced. The results of this study's Multi-Group SEM analysis demonstrated a significantly more influential causal association among students who had utilized the computers in schools. These results suggest that teacher support for computer use in schools should be both intentional and strategic (Julia & Dagmar, 2024; Korukluğlu & Yucel-Toy, 2022).

In contrast, this study found that the effect of science club activities on creative self-efficacy was significantly higher among students who did not use smartphones at secondary school. Similarly, Frohberg et al. (2009) confirmed the relatively insignificant effect of mobile learning and emphasized the necessity for teacher oversight and intervention. In light of the findings regarding significant differences in creative self-efficacy based on smartphone usage, it can be concluded that smartphone use has a more detrimental effect on fostering positive learning outcomes than on the diverse knowledge and information acquired through it. In this context, Hawi and Samaha (2016) expressed concerns about smartphone addiction in educational settings and empirically demonstrated that excessive smartphone use does not correlate with high academic achievement. Notably, many European countries have recently imposed restrictions on smartphone usage in schools due to concerns about distractions (Julia & Dagmar, 2024; UNESCO, 2023). The key is for teachers to acknowledge the potential issue that smartphone use in schools may lead to students' lack of self-control, while also recognizing that appropriate interventions for ICT use can foster resilience to uncertainty and enhance creative self-efficacy.

Conclusions and Implications

The purpose of the current study was to analyze the mediating effect of quality education provided by teachers in the association between science club activities and secondary school students' creative self-efficacy. The research findings confirmed that time-based and supportive teaching and learning in the classroom significantly enhance creative self-efficacy. Additionally, a key finding of this study revealed that secondary school students who had experience using the Internet at school tended to exhibit higher levels of creative self-efficacy due to their engagement in science club activities.

The research findings underscored the importance of quality educational considerations that teachers can implement beyond the standards of national-level education. This study demonstrated the significance of allocating sufficient time for thoughtful consideration and providing active support for creative and problem-solving learning activities, which are crucial for academic achievement. In particular, it is essential to emphasize that for science experiential activities to significantly enhance students' creative self-efficacy, continuous management and operational systems tailored to each school level (from elementary to secondary) must be established as a prerequisite. Furthermore, a long-term vision and educational strategy at the national level must be developed to broaden the effect of science education, extending from personal development to future career choices.

In addition, this study offered an opportunity to explore the positive effects and challenges associated with the culture of Internet use in schools. This has significant implications for how schools should adapt in the context of a digital society. The fact that many countries are implementing policies to ban the use of ICT in schools indicates that the negative effects of ICT use cannot be overlooked. Nevertheless, in light of this study and UNESCO's assertions within the international community, it is timely to minimize these negative effects and develop strategies for teachers to effectively manage ICT usage. Teachers should exercise caution to prevent students from using ICT indiscriminately, as it may hinder their engagement in learning. Moreover, for students' ICT use to contribute to positive academic achievement, teachers should first comprehend students' ICT literacy and the frequency of their usage. To this end, this study suggested that teachers engage with students on a daily basis and utilize the insights gained from these interactions as diagnostic data. And they should strive to leverage the accumulated student data to enhance their teaching strategies and improve their ability to implement classes that effectively utilize ICT. Therefore, the state and schools that lead the education system need to make efforts to create an environment that enables teachers to deliver quality education and enhances support for their professional roles. Educational institutions should not limit themselves to merely distributing ICT equipment; instead, they should

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closely integrate structural elements such as teacher training, curriculum development, and the cultivation of a positive school culture.

In this context, further research is necessary to explore the effect on student achievement at both the teacher and school levels. Given that students' use of ICT is more active outside of school as well as within it, it is essential to clarify the causal association between variables within the student-teacher-school-society structure from an ecological perspective. Additionally, follow-up research needs to consider that the effects of informal and non-formal education, alongside the formal education students receive at school, are closely interconnected.

It is also valuable to examine the types of change processes that occur in educational experiences using a qualitative approach. As students progress through different school levels, their cumulative experiences in science education may be assessed differently from their experiences at a cross-sectional level. By exploring longitudinal changes in creative self-efficacy in relation to their science learning experiences, educational institutions can develop more targeted support measures to enhance students' academic achievement.

Declaration of Interest

The authors declare no competing interests.

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THE ROLE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED QUESTION GENERATION ON PRESERVICE SCIENCE TEACHERS' 21ST-CENTURY TEACHING COMPETENCIES

Yusuf Zorlu

Abstract. *The increasing integration of artificial intelligence (AI) in education highlights the need to explore its impact on preservice science teachers' 21st-century teaching competencies. This study aimed to explore the role of AI-assisted question generation on preservice science teachers' 21st-century teaching competencies. Mixed-methods research design was utilized. This study was participated by 32 preservice science teachers. The "21st Century Skills Teaching Scale", "Tromsø Social Intelligence Scale", "Critical Thinking Disposition Scale", structured interview, and an evaluation rubric were administered as data collection tools. The integration of the generation process of AI-assisted questions was completed in a period of 12 weeks. In findings, the AI-assisted question generation process contributed to the enhancement of preservice science teachers' 21st century skills, social intelligence, and critical thinking disposition. The enhancement of 21st century skills, social intelligence, and critical thinking was concluded that the process of creating questions by utilizing the opportunities offered by artificial intelligence technology was thanks to interaction based on communication with artificial intelligence, cooperation established through group work, and access to up-to-date information through technology. In light of these findings, it could be stated that it will be beneficial to increase the integration of AI into teaching practices in science education.*

Keywords: *21st-century skills, artificial intelligence, critical thinking dispositions, social intelligence, preservice science teachers, science education*

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Introduction

The concept of artificial intelligence (AI) gained a theoretical foundation in 1950 through Alan Turing's work, in which he explored the possibility of thinking machines. It began to take shape as a distinct discipline in 1956, when John McCarthy introduced the term "artificial intelligence" in the lead-up to the Dartmouth Conference (Russell & Norvig, 2020). Since then, AI has evolved into one of the most influential technologies, addressed from various perspectives and described through multiple definitions. In the broadest sense, AI refers to the simulation or enhancement of cognitive abilities—such as reasoning, learning, thinking, and decision-making—typically associated with human intelligence, by computers (Demir, 2004; Luger, 2009; Nilsson, 2010; Wagner, 2024). It can also be characterized as an analytical life cluster designed to mimic human life (Gordon, 2011). According to Poole and Mackworth (2017), AI encompasses the ability to use information acquired from the environment to make decisions and interact with that environment. Overall, AI is a technology actively employed in numerous domains, including process optimization (Salkovska et al., 2024), increasing efficiency (Adams & Thompson, 2025), supporting decision-making processes (Wang, 2021), and delivering personalized environments (Jang & Choi, 2025).

AI has become a critical component, particularly by driving profound transformations in the field of education (Qin & Zhang, 2025). The use of AI in education offers various advantages, such as enhancing student achievement, adapting instructional materials, and supporting teachers in making data-informed decisions (Holmes et al., 2021). In their study on personalized learning, Hardaker and Glenn (2025) have emphasized that AI-based applications accommodate each student's individual learning styles, thereby fostering the development of personal competencies and providing a responsive and structured learning environment that promotes active student engagement. Similarly, Altun (2024) has highlighted that AI significantly contributes to pedagogical processes, such as personalized and adaptive learning, critical and creative thinking, as well as collaborative and simulation-based learning.

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These personalization capabilities render the learning process more adaptive and interactive. Al-Badi et al. (2022) have found that both students and educators hold positive attitudes toward AI in the context of personalized learning. In this regard, it is anticipated that AI may lead to changes in the roles of teachers in the future by assuming responsibilities such as attendance tracking, grade entry, basic knowledge delivery, and the customization of instructional materials (Bayındır, 2023).

In the educational context, AI is increasingly regarded as an innovative tool, particularly in science instruction, where it facilitates students' understanding of complex scientific concepts; supports higher-order cognitive skills (Bayram & Çelik, 2023); and enhances learning motivation and self-efficacy (Huang & Qiao, 2024). These contributions are of significant importance in alignment with the competencies expected from individuals in the 21st century. Referred to as "21st-century skills," these competencies are considered essential for individuals to adapt to the accelerating pace of global change (Gule et al., 2023; Herianto & Purwastuti, 2024). Due to the diversity of existing frameworks, there is no clear consensus on the precise definition of these skills, which are understood to be complex and multidimensional in nature (Chen, 2023). According to the OECD (2005), 21st-century skills fall under three primary categories: the interactive use of tools, the ability to engage with heterogeneous groups, and the capacity to act autonomously. Similarly, the Partnership for 21st Century Skills (P21) classifies them into three overarching domains: "learning and innovation skills", "information, media, and technology skills", and "life and career skills" (Partnership for 21st Century Skills, 2009). Although these skills have been approached from different focal points, they are fundamentally associated not only with students' possession of scientific knowledge but also with their ability to critically assess, apply, and integrate this knowledge through thinking, problem-solving, collaboration, and creativity. According to Scott (2015), the enhancement of 21st-century skills has been critical for individuals to contribute to societal well-being, which requires an accessible educational process that fosters high-level thinking, deep learning, and effective communication. In this regard, pedagogical practices that support the cultivation of 21st-century skills in educational settings are becoming increasingly prominent (Sullivan et al., 2020).

The effective utilization of 21st-century skills is not only contingent upon individual cognitive competencies but also closely linked to components of social intelligence, such as effective communication with others, understanding emotions, and engaging appropriately in social contexts (Wang et al., 2022). According to definitions by Bandura (2002) and Albrecht (2009), social intelligence is a multidimensional competency that enables individuals to develop behavior through interaction with environmental and personal factors, establish harmonious relationships with others, demonstrate empathy, and successfully apply these abilities across various domains of life. In this regard, social intelligence is directly associated with the process by which individuals comprehend the emotions, intentions, and behaviors of others, interpret this information, and develop appropriate social responses. It thus encompasses social awareness and social skills mediated through social cognition (Goleman, 2007; Silvera et al., 2001). As inherently social beings, humans engage and distinguish themselves through their capacity for social intelligence. A review of the relevant literature reveals an increasing emphasis on studies aimed at enhancing students' social intelligence (Platonova et al., 2021; Sailinova et al., 2024).

In the 21st century, one of the key pathways to cultivating qualified and talented individuals is placing critical thinking at the core of educational processes (Cui & Zhao, 2024; Fikriyatii et al., 2022). In this regard, researchers are increasingly emphasizing the significance of critical thinking in education in parallel with ongoing global developments (McPhee & Cox, 2024; Sutoyo et al., 2023). Consequently, the evolving conception of critical thinking emerges as an approach that supports pluralistic, inclusive, and serendipitous learning processes within the context of higher education (Kerruish, 2023). Wan (2022) has highlighted the need for greater efforts to effectively foster critical thinking. Therefore, the inclination toward critical thinking—which aims to develop individuals through approaches that question, analyze, and evaluate modes of thought—holds a vital place in contemporary educational paradigms. Facione (2000) has defined the disposition toward critical thinking as the willingness and tendency of individuals to engage in critical thought, and underscores the importance of nurturing this disposition.

Research Aim and Research Questions

There has been a notable increase in studies exploring the applications of AI in educational contexts. These studies encompass a wide range of dimensions, including teacher and student perceptions, academic achievement, motivation, and accessibility (AlKanaan, 2022; Al Darayseh, 2023; Su, 2022). Research conducted particularly in the field of science education has demonstrated that AI-supported applications effectively enhance learning processes. For instance, the accessible science laboratory developed by Watters et al. (2021) has highlighted the potential of inclusive education by facilitating the participation of visually impaired students in learning environments. Ad-

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ditionally, there are systematic (Almasri, 2024; Jia et al., 2024) and bibliometric (Genç & Koçak, 2024) studies that examine the role of AI in education. These investigations assess the potential of AI technologies and reveal their educational impacts. Similarly, within the domain of science education, significant research has been conducted with a focus on developing 21st-century skills. These studies emphasize the effectiveness of various instructional strategies in enhancing students' 21st-century competencies (Abaniel, 2021; Rethman et al., 2020).

The rapid increase in academic studies focusing on AI and education in recent years highlights the growing importance of examining the contributions of this technology to learning processes (Yun et al., 2025). Moreover, it is anticipated that AI will be used more extensively and effectively in the education in the future. However, at this point, it is evident that research on AI applications in science education remains quite limited. Indeed, in the context of higher education, it is emphasized that creating appropriate learning environments is critical for the effective adoption of AI (Tang et al., 2025). According to Antonenko and Abramowitz (2023), it has been essential that preservice teachers understand what AI is, as well as its role and potential in education, to use it effectively. Without adequate training and support, the full integration of AI into instructional processes cannot be achieved (Yılmaz, 2024). In this regard, there is a clear need for scientific research that contributes to addressing these issues. Accordingly, this study aimed to explore the role of AI-assisted question generation on preservice science teachers' 21st-century teaching competencies. Therefore, the research questions of this study are given below.

- What are the effects of AI-assisted question generation on preservice science teachers' enhancement of critical thinking, social intelligence, and 21st-century skills teaching?
- What are the relationships among preservice science teachers' critical thinking, social intelligence, and 21st-century skills teaching after AI-assisted question generation process?
- What are the preservice science teachers' views regarding AI-assisted question generation process?

In doing so, the study reveals the potential of AI-assisted applications on enhancing preservice teachers' social intelligence, critical thinking, and 21st-century competencies. Furthermore, by examining the multifaceted impacts of this process within the context of teacher education, the study aims to provide an original and timely contribution toward equipping future science teachers with the skills required in the digital age. Within this scope, the study is expected to be among the first of its kind to address the integration of AI-assisted practices in science education in a holistic manner—specifically in relation to social intelligence, 21st-century skills, and critical thinking dispositions—and to serve as a guide for future research in the field.

Research Methodology

Design

This study employed mixed-methods research design. Among quantitative methods, the one-group pretest post-test experimental design was utilized, while the phenomenological research method was adopted from qualitative approaches. In experimental design, participants are assessed with a pretest to measure the baseline status of a variable, followed by an experimental intervention. Subsequently, a post-test is administered to examine the change that occurred (Creswell & Creswell, 2022). The phenomenological research method, built upon a philosophical foundation, aims to explore the essence of individual lived experiences. Data are collected through interviews focused on participants' experiences, and during analysis, either descriptive or interpretative (hermeneutic) approaches are employed to identify common themes across participants' narratives (Creswell & Poth, 2016; Van Manen, 2016). In this study, experimental design was utilized to investigate the effects of the research process on preservice science teachers' critical thinking, social intelligence, and 21st-century skills. The phenomenological research method was employed to explore in detail their experiences and perceived competencies during the process of generation questions using AI. This study was completed in a period of 12 weeks.

Participants

The implementation of this study was structured around the content of the course Applications of Science in Technology. Therefore, preservice science teachers enrolled in the course "Applications of Science in Technology" were considered a suitable sample in terms of both data collection and implementation. Accordingly, a total of 32 preservice science teachers who took the course participated in this study. Participants were between 20 and 22 years of age and included 13 males and 19 females. They were briefed on the aim and procedures of the study, after which they voluntarily agreed to participate by giving informed consent.

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Data Collection Tools

For quantitative data collection, the "21st Century Skills Teaching Scale" (TCSTS), "Tromsø Social Intelligence Scale" (TSIS), and "Critical Thinking Disposition Scale" (CTDS) were used as data collection tools. For qualitative data, a structured interview form (IF) and an evaluation rubric (ERQAI) were utilized. The interview form was distributed to 32 preservice science teachers via Google Documents, and participants were asked to respond to the questions provided in the form.

The 21st Century Skills Teaching Scale (TCSTS) was originally developed by Jia et al. (2016) and later adapted into Turkish by Özyurt (2020). The TCSTS consists of 10 items and uses a 7-point Likert scale. It comprises three subscales: "Utility of Technology (UT)", "Collaboration (C)", and "Innova-tion-Problem Solving (IPS)". In Özyurt (2020) study, the reliability coefficient (Cronbach's alpha) for the overall scale was reported as .82. The reliability values for the subscales were .69 for UT, .69 for C, and .74 for IPS. In the present study, the re-liability coefficient of the overall scale was calculated as .92. The subscale reliabilities were .84 for UT, .77 for C, and .91 for IPS.

The "Tromsø Social Intelligence Scale" (TSIS) was developed by Silvera et al. (2001). The Turkish adaptation of the TSIS was carried out by Doğan and Çetin (2009). The scale consists of 21 items on a 5-point Likert scale. It comprises three subscales: "Social In-formation Processing (SIP)", "Social Skills (SS)", and "Social Awareness (SA)". In the study conducted by Doğan and Çetin (2009), the reliability coefficient (Cronbach's Alpha) for the overall scale was .83. The subscale reliabilities were reported as .77 for SIP, .84 for SS, and .67 for SA. In the present study, the reliability coefficient was calculated as .81 for the overall scale, while the subscale reliabilities were .80 for SIP, .75 for SS, and .71 for SA.

The "Critical Thinking Disposition Scale" (CTDS) was developed by Akın et al. (2015). The CTDS consists of 11 items and is based on a 5-point Likert scale. The scale consists of two subscales: "Critical Openness (CO)" and "Reflective Scepticism (RS)". In the study by Akın et al. (2015), the reliability of the scale (Cronbach's Alpha) was cal-culated as .78; and for the sub-factors, .68 for the CO factor and .75 for the RS fac-tor. In the present study, the reliability of the scale (Cronbach's Alpha) was calculated as .67; and for the sub-factors, .61 for the CO factor and .72 for the RS factor.

The Evaluation Rubric for Questions Prepared with AI (ERQAI) was prepared by researchers using ChatGPT, taking into account the aim and process of the study. The ERQAI was initially generated by the researcher using ChatGPT. Subsequently, necessary revisions were made based on a literature review (Ergün, Güler & **Çorlu**, 2011), and the final version of the rubric was established. The rubric was developed to evaluate the questions prepared by preservice science teachers with the support of AI. It consists of 10 items, each scored between one and four (see Table 1). Preservice science teachers receive a maximum of 40 points and a minimum of 10 points from ERQAI.

Table 1
Evaluation Rubric for Questions Prepared Using AI (ERQAI)

Evaluation Criterion	4 (Excellent)	3 (Good)	2 (Average)	1 (Needs Improvement)
1. Scientific Accuracy	All questions and options are scientifically accurate and based on up-to-date information. No incorrect information is present.	Most questions are scientifically accurate, but minor revisions may be needed.	Several scientific inaccuracies are present; some questions or options may contain incorrect information.	Many scientific errors are present; a significant portion of the questions include inaccurate information.
2. Relevance to the Topic	Questions are fully aligned with the selected science topic and cover it comprehensively.	Most questions are relevant to the topic, though some may not fully reflect it.	Only some of the questions reflect the topic; others may be unrelated or misleading.	Most questions are irrelevant or misleading; thematic integrity is not maintained.
3. Use of AI	AI tools were effectively used to generate creative and original questions.	AI tools were used well, but originality and creativity are limited.	AI tools were used, but contributed minimally. Questions remain basic.	AI tools were insufficiently used; questions appear to be created through traditional means.

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Evaluation Criterion	4 (Excellent)	3 (Good)	2 (Average)	1 (Needs Improvement)
4. Question Difficulty Level	Questions are balanced in difficulty and appropriate for different student levels, including various cognitive levels (knowledge, understanding, etc.).	Questions are generally of appropriate difficulty, but some may be too easy or too difficult.	The difficulty level is inconsistent; some questions are too easy, others too hard.	The difficulty level is inappropriate; most questions are either too difficult or too easy and do not match student level.
5. Validity and Reliability of Assessment	Questions accurately and consistently assess the intended learning outcomes.	Generally valid, though the validity of some questions may be questionable.	Questions partially assess the intended outcomes; a few may be off-target.	Weak validity; questions do not adequately assess the intended learning outcomes.
6. Variety of Question Types	Includes a balanced mix of multiple-choice, open-ended, matching, true–false, etc., assessing diverse thinking skills.	There is some variety, but certain question types may be missing or underrepresented.	Limited variety; mostly reliant on a single type of question.	Almost entirely composed of a single question type; lacks diversity.
7. Feedback and Learning Opportunities	Provides automated feedback via AI and offers learning opportunities after student responses; supports learning.	Some feedback is available, but not all questions provide it.	Feedback is limited, offering learning support for only a few questions.	No feedback or learning opportunities are provided; students may not learn from their mistakes.
8. Structural and Visual Organization of Questions	Questions are clearly structured and presented with visually balanced design; easy to understand and visually engaging for students.	Structure is generally good, though some questions could be better organized; visual design is adequate.	Structural confusion in some questions; presentation or visual layout may be unclear.	Poor structure; disorganized questions with little to no attention to visual design.
9. Applicability of Questions	Questions are designed to be compatible with different learning environments and levels of technology; effective in both digital and print formats.	Generally applicable, though implementation may be difficult in some settings.	Usable only in specific environments or with certain technologies; limited applicability.	Not broadly applicable; usable only under specific conditions.
10. Supporting Student Engagement	Questions are designed to attract student interest and support active participation through rich content and creative formats.	Generally engaging, though some questions may not sufficiently promote participation.	Limited engagement; questions may not stimulate active student involvement.	Fails to support engagement; questions are monotonous and unlikely to motivate students.

The Interview Form (IF) was prepared by the researchers using ChatGPT, taking into account the aim and process of the study. It was designed to identify the experiences of preservice science teachers regarding AI-assisted question generation. The IF consists of six open-ended questions:

1. How do you evaluate the process of preparing questions using artificial intelligence?
2. When you compare this process with previous traditional methods of question preparation, what differences do you observe?
3. What are the contributions of AI applications to the question preparation process? Can you provide examples?
4. Did you encounter any challenges or limitations while using AI during this process? If so, how did you overcome them?
5. Do you consider yourself competent in using AI technology during this process? Do you think you need further training?
6. Do you have any additional suggestions regarding this process?

Intervention

The implementation process and design are presented in Figure 1.

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Figure 1
Implementation Process and Design

1st Week: Preparation & Pre-tests	*•The study was introduced and participants were informed. A WhatsApp group was created for the implementation process. Participants were randomly divided into four groups. Pre-tests of TCSTS, TSIS, and CTDS were administered.*
2nd–3rd Weeks: Orientation & Topic Assignment	•Participants were informed about AI and the use of ChatGPT. Topics related to "Applications of Science in Technology" were assigned to each group by the researchers: – Pharmaceutical and Cosmetic Product Technologies (Group 1) – Water Production Technologies (Group 2) – Stem Cell Technology (Group 3) – Processed Food Technologies and Their Applications (Group 4)
4th Week: Group Work & Presentation Preparation	•Groups conducted research on their assigned topics and collaborated to prepare their presentations.
5th–6th Weeks: Group Presentations	•Each group presented their prepared content in the classroom environment.
7th Week: Question Preparation Using ChatGPT	•Groups prepared questions related to their assigned topics using ChatGPT.
8th–9th Weeks: Presentation of Questions & Feedback	•Groups presented the questions they generated in the classroom. They received feedback from the researcher and other groups.
10th–11th Weeks: Revision of Questions & Evaluation	•Based on the feedback, groups revised their questions and uploaded them to the WhatsApp group. Other groups evaluated the questions using the ERQAI rubric. The Interview Form (IF) was also applied.
12th Week: Post-tests	*•Post-tests of TCSTS, TSIS, and CTDS were administered.*

In the first week, the study was introduced to the participants, and relevant information was shared. Pre-tests of the "21st Century Skills Teaching Scale" (TCSTS), the "Tromsø Social Intelligence Scale" (TSIS), and the "Critical Thinking Disposition Scale" (CTDS) were administered. Participants were then divided into four groups, each consisting of eight preservice science teachers. A WhatsApp group was established to support communication and ensure participation throughout the implementation process.

In the second and third week, participants were informed about artificial intelligence and the use of ChatGPT. Topics related to the applications of science in technology were introduced, and four out of ten preselected subtopics were assigned to the groups. The assigned topics were as follows:

- Group 1: "Pharmaceutical and Cosmetic Product Technologies"
- Group 2: "Water Production Technologies"
- Group 3: "Stem Cell Technology"
- Group 4: "Processed Food Technologies and Their Applications"

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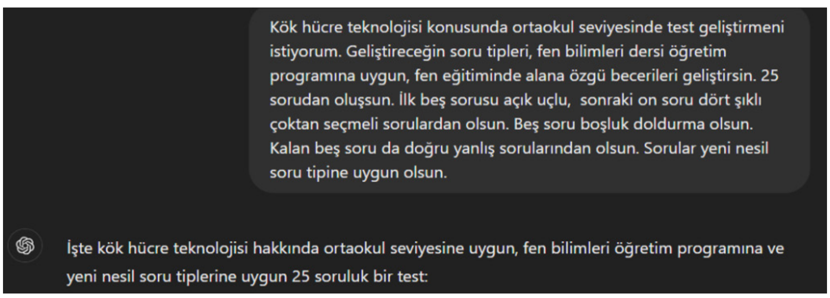
In the fourth week, each group collaborated on their assigned topic over the course of one week (two class hours in total) to prepare a presentation and detailed documents using scientific sources.

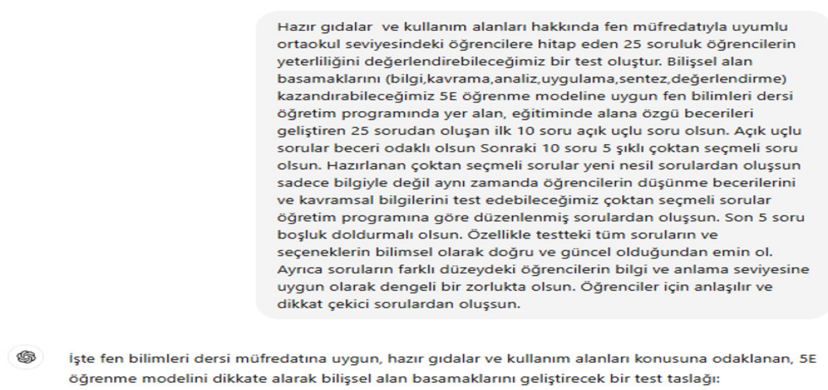
In the fifth week and sixth week, these presentations were delivered during a one-class-hour session in Weeks 5 and 6.

In the seventh week, following the presentations, groups engaged in another week of collaborative work (two class hours) to generate 25 multiple-choice questions using the AI tool ChatGPT, based on the topics they had previously presented. Preservice science teachers used the documents they prepared on the subjects of the "Applications of Science in Technology" course to generate questions in the ChatGPT. This approach helped ensure that the questions produced contained accurate and complete scientific information. While using the free version of ChatGPT, limitations such as the inability to generate visuals were addressed by providing sample question types and revising the generated content through the platform. Through these revisions and examples, questions were enriched with visual elements and diversified content where needed. Examples of how prompts were entered into ChatGPT are presented in Table 2. (Each week included two class hours, totaling 100 minutes.)

Table 2

Examples of Entering Prompts into ChatGPT in Phase 1

<table>
<tr><td>Group 3</td><td>

English Translation I want you to develop a test on stem cell technology at the middle school level. The question types you will develop should be appropriate for the science course curriculum and should develop field-specific skills in science education. It should consist of 25 questions. The first five questions should be open-ended, and the next ten questions should be four-option multiple choice questions. Five questions should be filled in the blanks. The remaining five questions should be true or false questions. The questions should be appropriate for the new generation question type.</td></tr>
<tr><td>Group 4</td><td>

English Translation: Create a test that will evaluate the competence of students with 25 questions that are compatible with the science curriculum about ready-made foods and their usage areas and appeal to middle school students. The first 10 questions consisting of 25 questions that are in the science course curriculum that is suitable for the 5E learning model where we can gain cognitive domain steps (knowledge, comprehension, analysis, synthesis, evaluation) and that develop field-specific skills in education should be open-ended questions. Open-ended questions should be skill oriented. The next 10 questions should be 5-option multiple choice questions. The prepared multiple-choice questions should consist of new generation questions and should consist of multiple-choice questions that will test not only knowledge but also students' thinking skills and conceptual knowledge. The last five questions should be fill-in-the-blank. Make sure that all questions and options in the test are scientifically correct and up to date. In addition, the questions should have a balanced difficulty level that is suitable for the knowledge and understanding levels of students at different levels. They should consist of understandable and eye-catching questions for students.</td></tr>
</table>

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In the eighth week and ninth week, the groups presented both the questions they had prepared and the preparation process during a one-class-hour session (50 minutes). Subsequently, the multiple-choice questions they created were reviewed, and feedback was provided by the researchers and other preservice science teachers.

In the tenth week and eleventh week, based on the feedback, the groups finalized their multiple-choice questions and uploaded them to the WhatsApp group (1 week – 2 class hours). Examples of entering prompts, reviewing, and editing questions generated into ChatGPT are given in Table 3. Then, each group evaluated the questions prepared by the other groups using the ERQAI. At the same time, the researchers also assessed the questions using the ERQAI (1 week – 2 class hours). The preservice science teachers' views regarding the AI-assisted question preparation process were collected through a form created via Google Forms.

Table 3

Examples of Entering Prompts, Reviewing, and Editing Questions Generated into ChatGPT in Phase 2

Group 1	Açık uçlu soruları orta okul seviyesine uygun olarak öğrencilerin yorum yapabileceği sorulardan oluştur. Tabii, açık uçlu soruları daha ortaokul seviyesine uygun hale getirecek şekilde, öğrencilerin günlük yaşamla bağlantı kurarak yorum yapabileceği şekilde düzenleyebilirim. İşte bu şekilde revize edilmiş açık uçlu sorular: **English Translation:** Create open-ended questions that are appropriate for the middle school level and that students can comment on.
	Çoktan seçmeli soruları sadece bilgiye dayalı değil de, öğrencilerin akıl yürütebileceği uzun sorulardan oluştur. Elbette! Öğrencilerin sadece bilgiye dayalı değil, aynı zamanda akıl yürütme becerilerini geliştirecek, daha uzun ve düşünmeye teşvik eden çoktan seçmeli sorular hazırlayacağım. Bu tür sorular, öğrencilerin konuyu daha derinlemesine düşünmelerini ve sonuçlar hakkında mantıklı tahminlerde bulunmalarını sağlayacaktır. **English Translation:** Make multiple choice questions longer, not just based on knowledge, but on questions that allow students to reason.
Group 2	10 çoktan seçmeli soruların 2 tanesinde bana bir tablo oluştur bu tabloda doğru ve yanlış önermeler bulunsun ve bu önermeler üzerinden 4 şık oluştur Aşağıda su üretim sistemleriyle ilgili iki adet çoktan seçmeli soru için tablo oluşturdum. Her tabloda doğru ve yanlış önermeler bulunmakta ve bunlardan yola çıkarak oluşturulan 4 şıkkı bulabilirsiniz. **English Translation:** Create a table for me in 2 of the 10 multiple choice questions. This table contains true and false statements and create 4 options based on these statements.
Group 3	Bu sorular öğrencilerin bilgiyi sadece kullanmalarını değil aynı zamanda analiz etmelerini yorum yapmalarını ve olaylar arasındaki bağlantı kurmasını sağlasın. Her bir öğrencinin kök hücre ile ilgili kavramları anlamalarını ve bu kavramların gerçek dünya durumlarına uygulanmasını amaçlasın. Çoktan seçmeli soruların şıkları biraz daha çeldirici olsun. Bellek güncellendi İşte kök hücre teknolojisi hakkında öğrencilerin analiz yapmalarını, yorumlamalarını ve olaylar arasında bağlantı kurmalarını sağlayacak şekilde tasarlanan, gerçek dünya uygulamalarına yönelik yeni sorular: **English Translation:** These questions should not only require students to use information but also to analyze, interpret, and make connections between events. They should aim for each student to understand stem cell concepts and apply these concepts to real-world situations. The options for multiple-choice questions should be a bit more challenging.

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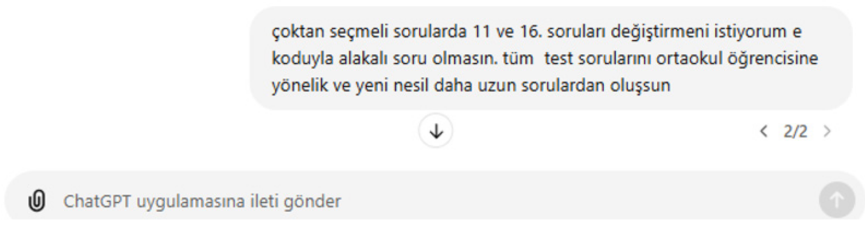
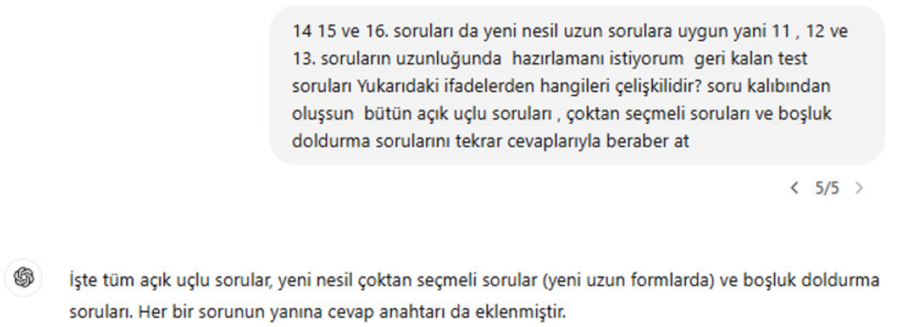
Group 4



English Translation: I want you to change questions 11 and 16 in the multiple-choice questions. There should be no questions related to the E code. All test questions should be aimed at middle school students and consist of new generation longer questions.



English Translation: I want you to prepare questions 14, 15 and 16 in line with the new generation long questions, that is, the length of questions 11, 12 and 13. The remaining questions should consist of the question pattern. Which of the above statements are contradictory? Write all the open-ended questions, multiple choice questions and fill-in-the-blank questions together with the answers again.

In the twelfth week, the post-tests of TCSTS, TSIS, and CTDS were administered.

Ethical Issues

To reduce the potential influence of external variables on the participants, the data collection process was carefully designed. Moreover, ethical approval for the study was granted by the ethics committee of the university affiliated with the second author (Approval Date: 27.11.2024; Meeting No: 2024/11; Document No: 522).

Data Analysis

The qualitative data obtained from the study were analyzed using content analysis. The collaboration was made with an academician (associate professor) who specialized in science education. To determine whether the pretest and posttest data for the TCSTS, TSIS, and CTDS followed a normal distribution, descriptive statistics and normality values were examined. The results are presented in Table 4.

Table 4
Descriptive and Normality Values of TCSTS, TSIS, and CTDS

Descriptive and Normality Values	TCSTS		TSIS		CTDS	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Mean	51.66	60.56	77.38	92.50	42.31	49.59
Skewness	.284	-.315	-.069	.964	-.575	-.245
Std. Error of Skewness	.414	.414	.414	.414	.414	.414
Kurtosis	-.739	-.450	-.863	.742	-.464	-.415

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Descriptive and Normality Values	TCSTS		TSIS		CTDS	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Std. Error of Kurtosis	.809	.809	.809	.809	.809	.809
Shapiro-Wilk p	.428	.281	.088	.065	.070	.437

The skewness and kurtosis values of the data obtained from the TCSTS, and its subscales were found to be between -1 and +1, and the ratios of skewness value/skewness standard error and kurtosis value/kurtosis standard error were within the range of -1.96 to +1.96. According to Morgan et al. (2004), skewness and kurtosis values within the range of -1 to +1 indicate normal distribution. Similarly, Can (2014) states that if the ratios of skewness/standard error and kurtosis/standard error fall between -1.96 and +1.96, the data distribution can be considered normal. In addition, normality was tested using the Shapiro–Wilk test, and the results confirmed that the data were normally distributed ($p > .05$). The quantitative data obtained from the TCSTS, TSIS, and CTDS were analyzed using the paired samples t-test.

The data obtained from the rubric were analyzed descriptively. Peer evaluation was conducted within the scope of the research. Each group evaluated the questions prepared by the other groups using the Evaluation Rubric for Questions Prepared with AI (ERQAI). The final scores were determined by calculating the average of the groups' evaluation scores and the researchers' evaluation scores. The data obtained from the interview form were analyzed using content analysis, one of the qualitative data analysis methods, first independently by two field experts (Associate Professors in Science Education), and then collaboratively. When they came together, differing points were identified and finalized based on consensus. To determine the reliability of the qualitative data analysis, the formula "Reliability = Agreement / (Agreement + Disagreement) × 100" was applied (Miles & Huberman, 1994). For the structured interviews, the agreement between the two coders was calculated as: 264 / (264 + 32) × 100 = 89.19%. According to this value, reliability was ensured.

Research Results

Paired samples t-tests were employed to examine whether the differences between preservice science teachers' pre-test and post-test scores on the TCSTS, TSIS, and CTDS were statistically significant. The findings of these analyses are presented in Table 5.

Table 5
Paired Samples t-Test results for TCSTS, TSIS, and CTDS

Scale	Test	*N*	*M*	*SD*	*df*	*t*	*p*
TCSTS	Pre-test	32	51.66	4.76	31	24.535	< .001
	Post-test	32	60.56	6.29			
TSIS	Pre-test	32	77.38	2.39	31	40.047	< .001
	Post-test	32	92.50	3.86			
CTDS	Pre-test	32	42.31	4.06	31	17.882	< .001
	Post-test	32	49.59	2.88			

An examination of Table 5 reveals that there are statistically significant differences in favor of preservice science teachers' the post-test scores on the TCSTS, TSIS, and CTDS (TCSTS: $t_{(31)} = 24.535$, $p < .001$; SIS: $t_{(31)} = 40.047$, $p < .001$; CTDS: $t_{(31)} = 17.882$, $p < .001$).

Paired samples t-tests were conducted to determine whether there were statistically significant differences between the preservice science teachers' pre-test and post-test scores on the subscales of the TCSTS, TSIS, and CTDS. The results are presented in Table 6.

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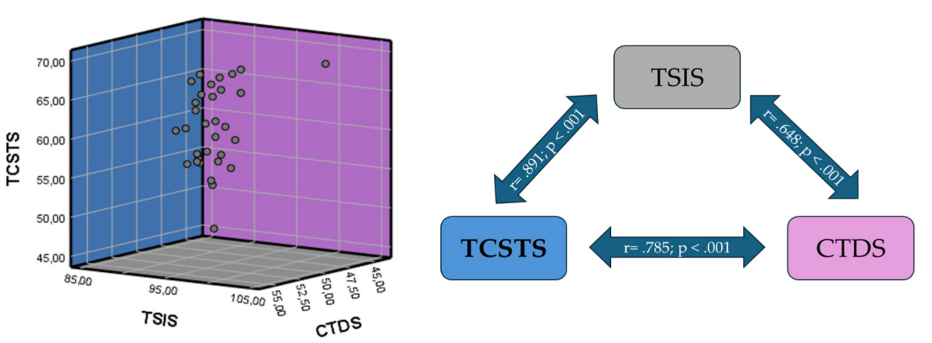
Table 6
Paired Samples T-Test Results for the Subscales of the TCSTS, TSIS, and CTDS

Scale	Subscales		N	*M*	*SD*	*df*	*t*	*p*
TCSTS	UT	Pre-test	32	15.53	1.80	31	8.288	< .001
		Post-test	32	18.16	2.16			
	C	Pre-test	32	16.22	2.00	31	9.435	< .001
		Post-test	32	18.56	2.00			
	IPS	Pre-test	32	19.91	2.05	31	11.143	< .001
		Post-test	32	23.84	2.97			
TSIS	SIP	Pre-test	32	26.50	1.34	31	20.193	< .001
		Post-test	32	33.63	2.28			
	SS	Pre-test	32	23.00	1.24	31	18.922	< .001
		Post-test	32	27.69	1.03			
	SA	Pre-test	32	27.88	1.48	31	9.820	< .001
		Post-test	32	31.19	1.58			
CTDS	RS	Pre-test	32	16.25	1.74	31	5.135	< .001
		Post-test	32	17.91	1.51			
	CO	Pre-test	32	26.06	2.97	31	16.931	< .001
		Post-test	32	31.69	2.09			

An examination of Table 6 reveals that there are statistically significant differences in favor of the preservice science teachers' post-test scores on the subscales of the TCSTS, TSIS, and CTDS (UT: $t_{(31)} = 8.288$, $p < .001$; C: $t_{(31)} = 9.435$, $p < .001$; IPS: $t_{(31)} = 11.143$, $p < .001$; SIP: $t_{(31)} = 20.193$, $p < .001$; SS: $t_{(31)} = 18.922$, $p < .001$; SA: $t_{(31)} = 9.820$, $p < .001$; RS: $t_{(31)} = 5.135$, $p < .001$; CO: $t_{(31)} = 11.143$, $p < .001$).

In order to determine whether there were statistically significant relationships between the preservice science teachers' post-test scores on the TCSTS, the TSIS, and the CTDS, a Pearson correlation analysis was conducted. The findings are presented in Figure 2.

Figure 2
Pearson Correlation Analysis among the Post-Test Scores of TCSTS, TSIS, and CTDS



An examination of the Pearson correlation analysis presented in Figure 2 reveals that there are statistically significant and strongly positive relationships among the preservice science teachers' post-test scores on the TCSTS, TSIS, and CTDS (TCSTS–TSIS: $r = .891$, $p < .001$; TCSTS–CTDS: $r = .785$, $p < .001$; TSIS–CTDS: $r = .648$, $p < .001$).

A Pearson correlation analysis was performed to explore the statistically significant associations among preservice science teachers' post-test scores on the subscales of the TCSTS, TSIS, and CTDS. The findings are presented in Table 7.

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Table 7.
Pearson Correlation Analysis Among the Subscales of the TCSTS, TSIS, and CTDS

Scale	Scale		TCSTS			TSIS			CTDS	
	Subscales		UT	C	IPS	SIP	SS	SA	RS	CO
TCSTS	UT	*r*	1							
		p								
	C	*r*	.749**	1						
		p	p < .001							
	IPS	*r*	.632**	.730**	1					
		p	p < .001	p < .001						
TSIS	SIP	*r*	.681**	.668**	.742**	1				
		p	p < .001	p < .001	p < .001					
	SS	*r*	.778**	.868**	.837**	.772**	1			
		p	p < .001	p < .001	p < .001	p < .001				
	SA	*r*	.504*	.708**	.578*	.697**	.694**	1		
		p	.003	p < .001	.001	p < .001	p < .001			
CTDS	RS	*r*	.797**	.896**	.887	.850**	.914**	.672**	1	
		p	p < .001	p < .001	p < .001	p < .001	p < .001	p < .001		
	CO	*r*	.829**	.868**	.782**	.727**	.869**	.657**	.912**	1
		p	p < .001	p < .001	p < .001	p < .001	p < .001	p < .001	p < .001	

* $p < .05$; ** $p < .01$

An examination of the Pearson correlation analysis in Table 7 indicates that there are statistically significant moderate positive correlations ($r > .30$, $p < .05$) between the SA subscale of the TSIS and the UT and IPS subscales of the TCSTS based on post-test scores. Moreover, strong positive and statistically significant relationships ($r > .60$, $p < .01$) were found among the post-test scores of the remaining subscales of the TCSTS, TSIS, and CTDS.

The results of ERQAI of the questions prepared by preservice science teachers using AI are presented in Figure 3.

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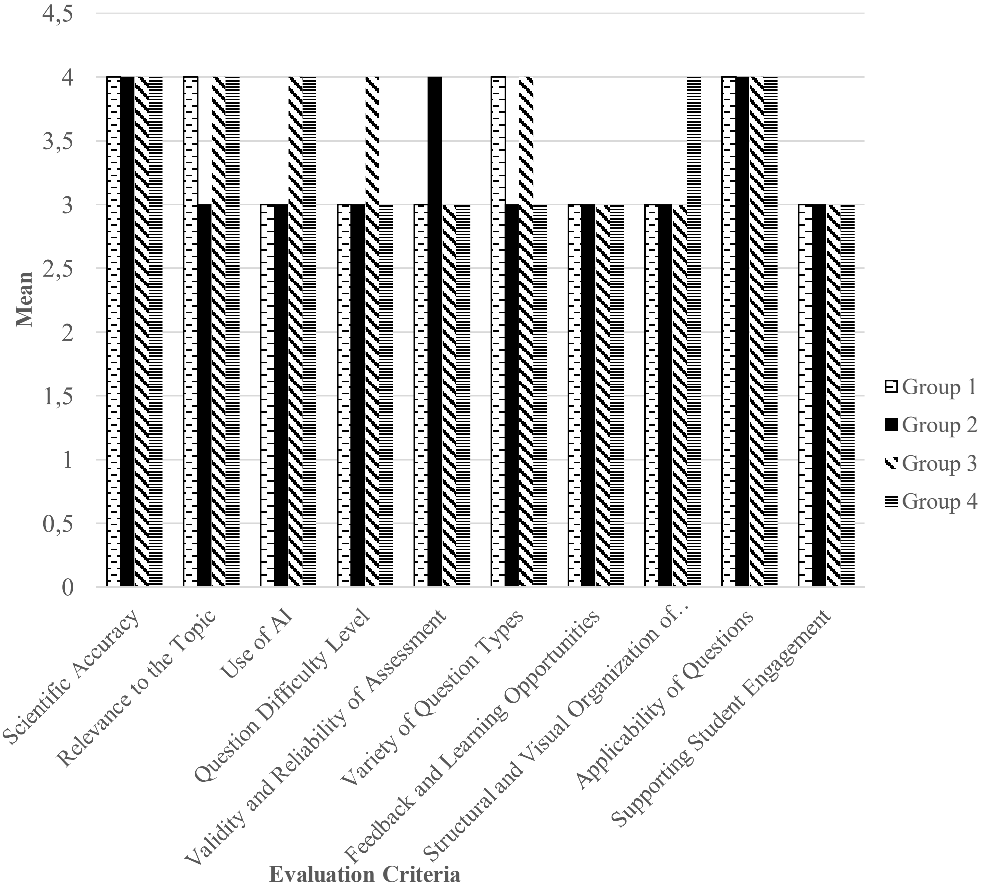
Figure 3
The ERQAI of the Questions Prepared by Preservice Science Teachers Using AI



According to the data presented in Figure 2, the total rubric scores for the questions prepared by preservice science teachers using ChatGPT range between 33 and 36. This indicates that, in general, the arithmetic means of participants' performance across evaluation criteria mostly falls within the 3 to 4-point range. All groups received a score of 4 in the "*Scientific Accuracy*" and "*Applicability of Questions*" categories. In the "*Relevance to the Topic*" category, Group 2 received a score of 3, while the other groups scored 4. In the "*Use of AI*" category, Groups 1 and 2 received a score of 3, while the remaining groups received a score of 4. In the "*Variety of Question Types*" category, Groups 2 and 4 scored 3, whereas the others received 4. For the "*Level of Difficulty*" category, Group 3 scored 4, while the other groups received 3. In the "*Validity and Reliability of Assessment*" category, Group 2 scored 4, and the remaining groups scored 3. For the "*Structural and Visual Organization of Questions*" category, Group 4 received a score of 4, while the other groups received 3. In both the "*Feedback and Learning Opportunities*" and "*Supporting Student Engagement*" categories, all groups received a score of 3. Examples of the questions prepared by the preservice science teachers are provided in Table 8.

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Table 8
Examples of Questions Prepared with the Use of AI

<table>
<tr><th>Group</th><th>Question Type</th><th>Question(s)</th></tr>
<tr><td>1</td><td>True–False</td><td>- To increase the effectiveness of drugs, it is always necessary to take an overdose.
- Cosmetic products can help ensure that the skin appears healthy and smooth.</td></tr>
<tr><td>2</td><td>Multiple Choice</td><td>A. Reverse osmosis is the most effective method for desalinating water.
B. The chlorination process is used to remove heavy metals from water.
C. Filtration removes solid particles from water.
D. Biological purification methods purify water without using chemicals.
Which of the above statements is correct?
a) A and C b) B and D c) A and D d) B and C</td></tr>
<tr><td></td><td>Matching</td><td>Column A Column B
1. Filtration A. Destroys microorganisms without chemicals
2. Ion Exchange B. Removes large particles in water
3. Reverse Osmosis C. Passes water through a semi-permeable membrane
4. UV Disinfection D. Reduces water hardness through ion exchange
Match Column A with Column B.</td></tr>
<tr><td>3</td><td>Informational + Multiple Choice</td><td>Text: Stem cells have the capacity to transform into different cell types. Thanks to this, they can be used to repair diseased organs and tissues.
Question: According to the text, what are stem cells used for?
A) To regulate body temperature
B) To repair diseased tissues and organs
C) To speed up digestion
D) To reduce muscle fatigue</td></tr>
<tr><td></td><td>Informational + Multiple Choice</td><td>Text: Embryonic stem cells can become any cell type, but obtaining them requires destruction of the embryo, leading to ethical concerns. Adult stem cells have more limited capacity.
Question: According to the text, what is the main ethical issue in using embryonic stem cells?
A) Their slow reproduction
B) Embryo destruction required
C) Limited to specific cell types
D) Accessibility to all people</td></tr>
<tr><td></td><td>Table-Based Choice</td><td>The table below lists possible areas of future progress in stem cell therapies. Considering the areas in the table, select the area in which stem cell therapies are expected to make the greatest progress.
Table: Areas of Potential Progress in Stem Cell Treatments
<table>
<tr><td>Area</td><td>Potential Progress</td></tr>
<tr><td>Early detection of genetic diseases</td><td>Medium</td></tr>
<tr><td>Personalization of diet plans</td><td>Low</td></tr>
<tr><td>Repair of broken bones</td><td>Medium</td></tr>
<tr><td>Treatment of serious diseases such as cancer</td><td>High</td></tr>
</table>
A) Early detection of genetic diseases
B) Personalization of diet plans
C) Repair of broken bones
D) Treatment of serious diseases such as cancer</td></tr>
<tr><td>4</td><td>Open-Ended</td><td>1. Elif is preparing a school project on nutrition and researching the role of processed foods. Before asking her classmates whether these foods are healthy, what should she learn? Explain the healthy and unhealthy aspects of processed foods with examples.
2. During grocery shopping, Ali's family reads the labels on packaged foods carefully. Ali is curious about the terms "calorie," "protein," and "carbohydrate." How would you explain these terms and why they are important?</td></tr>
<tr><td></td><td>Multiple Choice</td><td>Scenario: While shopping, Ayşe saw "contains no additives" on a juice label but noticed additional ingredients in the list.
Question: What is the most accurate explanation for Ayşe about label interpretation and additives?
A) The statements on the label are generally marketing strategies; the list of ingredients should be checked.
B) Additives are only natural and always healthy.
C) Additives are always harmful and must be avoided.
D) "No additives" means the product contains no chemicals at all.
E) The color of the package is more reliable than the ingredient list.</td></tr>
</table>

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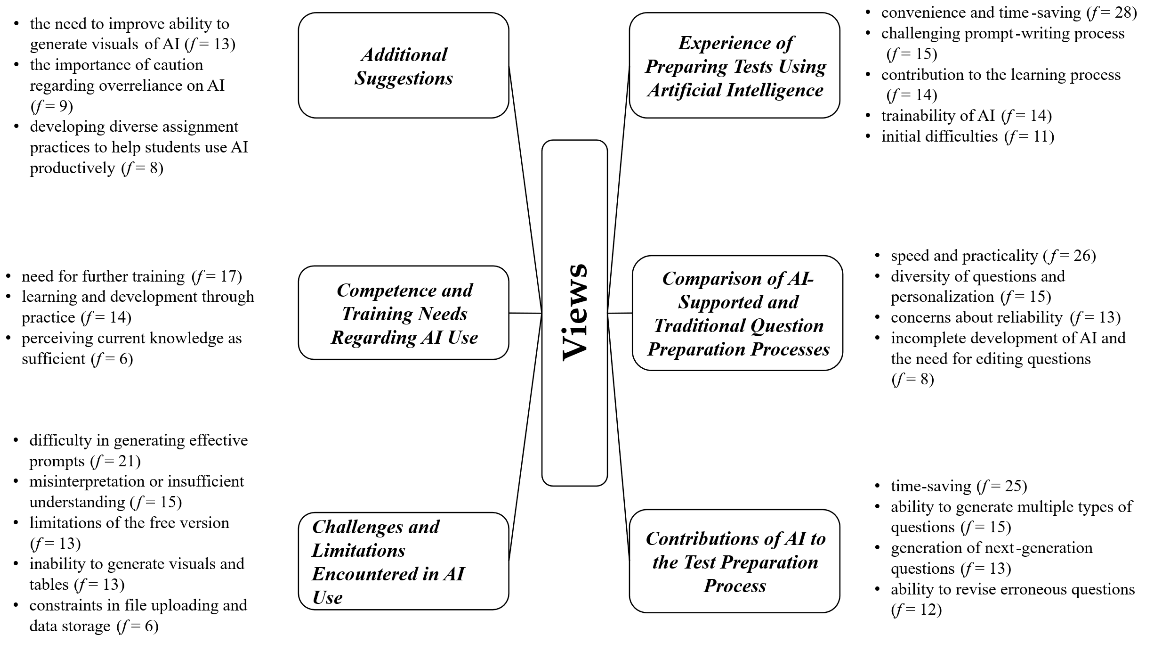
The content analysis of preservice science teachers' views on the generating questions using artificial intelligence is presented in Figure 4.

Figure 4
Preservice Science Teachers' Views on Preparing Questions Using AI



The content analysis of preservice science teachers' views on generating questions using artificial intelligence, as presented in Figure 4, reveals six themes: "*Experience of Preparing Tests Using Artificial Intelligence*", "*Comparison of AI-Supported and Traditional Question Preparation Processes*", "*Contributions of AI to the Test Preparation Process*", "*Challenges and Limitations Encountered in AI Use*", "*Competence and Training Needs Regarding AI Use*", and "*Additional Suggestions*". Within the theme "*Experience of Preparing Tests Using Artificial Intelligence*", the following codes were identified: "convenience and time-saving" (f = 28), "challenging prompt-writing process" (f = 15), "contribution to the learning process" (f= 14), "trainability of AI" (f = 14), and "initial difficulties" (f = 11). Preservice science teachers stated that AI saves time in question preparation and accelerates the process; that creating effective prompts is challenging and time-consuming; that AI can be trained and requires learning for effective use; and that they experienced difficulties when first starting to prepare tests using AI.

> "*Preparing questions using artificial intelligence saves time. The questions are comprehensive, accurate, and quite strong in terms of variety. AI can generate different types of questions such as open-ended, fill-in-the-blank, multiple choice, survey, and true–false. However, when creating questions with AI, we need to work on developing and refining the questions to a certain level. The more we improve them, the higher the quality becomes. What really matters here is how we ask the questions to the AI. In short, the questions should be phrased in a way that the AI can understand—no spelling mistakes, proper punctuation, and expressed in a clear and detailed manner. The process of preparing questions with AI offers significant advantages in terms of both ease and time.*" (PST15)

Within the theme "*Comparison of AI and Traditional Question Preparation*", the following codes were identified: "speed and practicality" (f = 26), "diversity of questions and personalization" (f = 15), "concerns about reliability" (f = 13), and "incomplete development of AI and the need for editing questions" (f = 8). Preservice science teachers expressed that AI is faster and more practical than traditional test preparation methods; however, because AI can generate misleading or convincingly incorrect information, they regarded traditional question preparation methods as more reliable. They also noted that AI is capable of generating various types of questions and adapting them to the appropriate student level, but due to its incomplete development, the generated questions require further editing.

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"*Personally, I still trust traditional methods more, because AI can make very convincing mistakes. It can be very challenging to identify those errors, but this approach is, in every sense, much more cost-effective. The traditional method may be a bit more laborious, yet it is more reliable*." (PST3)

"*It produces content in a more original and creative manner in a short period. It can generate questions with varying levels of difficulty according to the students' proficiency*." (PST10)

Within the theme "*Contributions of AI to the Question Preparation Process*", the following codes were identified: "time-saving" ($f = 25$), "ability to generate multiple types of questions" ($f = 15$), "generation of next-generation questions" ($f = 13$), and "ability to revise erroneous questions" ($f = 12$). Preservice science teachers reported that, compared to traditional question preparation processes, they were able to create questions in significantly less time; that AI enabled the creation of logic-based and multidimensional questions; and that it could identify faulty questions and provide suggestions for corrections.

"*When preparing questions, AI tailors them to the students' levels and needs. It offers high diversity and creativity in question types. It generates answer keys and detects incorrect questions. For example, in a test, it identifies improperly worded questions, explains why they are incorrect, and suggests corrections. It can also focus on a topic a student is struggling with and generate questions that progress from simple to complex*." (PST12)

"*Its contribution to the test preparation process is mainly in terms of saving time and offering multiple question formats. I believe I can now prepare a test in 3 to 5 hours, whereas traditionally this process would take weeks. With AI, it is possible to generate a wide range of question types.*" (PST28)

Within the theme "*Challenges and Limitations Encountered in AI Use*", the following codes were identified: "difficulty in generating effective prompts" ($f = 21$), "misinterpretation or insufficient understanding" ($f = 15$), "limitations of the free version" ($f = 13$), "inability to generate visuals and tables" ($f = 13$), and "constraints in file uploading and data storage" ($f = 6$). Preservice science teachers reported that achieving accurate results often required extensive trial and error; that AI sometimes misunderstood prompts or produced incomplete or incorrect outputs; that its ability to generate visuals and tables for test materials was inadequate; and that there were limitations regarding file uploads and retention of previous data.

"*Since we used the free version, our access was limited. It was difficult to insert tables or images into the questions*." (PST6)

"*There were challenges—particularly with prompt creation. Finding the right prompt is difficult. I overcame this through hours of trial and error. A major limitation is that I don't use the premium version of GPT, so I can only enter a new prompt every three hours and have to remind it of the previous ones manually. That's where the difficulty lies.*" (PST21)

Within the theme "*Competence and Training Needs Regarding AI Use*", the following codes were identified: "need for further training" ($f = 17$), "learning and development through practice" ($f = 14$), and "perceiving current knowledge as sufficient" ($f = 6$). Most preservice science teachers indicated a need for more training in order to use AI effectively; they emphasized the importance of hands-on experience in mastering AI use; while some participants stated that their existing knowledge was sufficient for using AI in question preparation.

"*I definitely need more training on this. I don't think I fully understand the language of AI—or maybe it doesn't understand me.*" (PST1)

"*I believe I have gained knowledge about AI technology during this process, especially regarding how to prepare test questions. However, I think I could prepare better questions if I received more training.*" (PST27)

Within the theme "*Additional Suggestions*", the following codes were identified: "the need to improve ability to generate visuals of AI" ($f = 13$), "the importance of caution regarding overreliance on AI" ($f = 9$), and "developing diverse assignment practices to help students use AI productively" ($f = 8$). Preservice science teachers emphasized that while AI is becoming increasingly widespread, especially in completing assignments given by instructors or teachers, it is essential to guide students toward using AI collaboratively and meaningfully—rather than as a shortcut. They suggested that similar to the question-generation task, assignments could be designed to encourage active engagement with AI. Additionally, they highlighted the need for critically reviewing AI-generated content and providing precise instructions and ongoing feedback to ensure quality outcomes.

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"*AI is becoming increasingly widespread nowadays. Many students complete their assignments using AI tools. To prevent misuse and encourage productive use of AI, assignments-like the test development task-can be designed to foster collaboration with AI. This way, we can use AI not just to complete tasks, but to understand and benefit from it.*" (PST7)
"*The content we obtain from using AI should always be reviewed. After preparing the questions, we need to give constant feedback to get good results, and we must provide clear instructions to achieve effective outcomes.*" (PST19)

Discussion

In this study, the role of AI-assisted question generation in the enhancement of social intelligence, critical thinking disposition, and 21st-century skills was investigated. In line with this objective, the findings obtained from the research were presented and discussed within the framework of the relevant literature. Based on the results of the study, several recommendations were made for future research.

In the post-test results of the 21st Century Skills Teaching Scale (TCSTS) and its subscales ("Perceived Usefulness of Technology", "Collaboration", and Innovation and Problem Solving"), it was found that the scores of the preservice science teachers' post-test scores were higher than their pre-test scores and that the difference was statistically significant. Based on the findings, it can be stated that the AI-assisted question generation process contributed to the enhancement of the preservice science teachers' 21st-century skills. In this improvement, several factors played a role: the support provided during the question preparation process by utilizing the opportunities offered by AI technology, communication-based interaction with AI, collaboration established through group work, and access to up-to-date information through technology. When the preservice science teachers' views are examined in the IF, it is seen that they stated AI facilitated the question generation process, saved time, provided practicality, allowed for the creation of various types of questions, contributed to the learning process, and enabled the correction of faulty questions. According to their views, the main benefits provided by AI technology in the AI-assisted question preparation process include time saving, practicality, and the creation of a productive learning environment. This process enabled preservice teachers to practically develop key 21st-century skills. The results obtained from the study are supported by relevant literature (Al-Badi et al., 2022; Altun, 2024; Bayram & Çelik, 2023; Hardaker & Glenn, 2025). In the study by Hardaker and Glenn (2025), it was stated that AI-based applications enable the enhancement of students' skills and abilities and provide a learning environment that encourages active participation. Similarly, Altun (2024) emphasizes that AI makes significant contributions to learning, critical and creative thinking, collaborative and technology-supported learning processes in education. Al-Badi et al. (2022) revealed that students have positive attitudes toward AI. The preservice science teachers expressed that through interacting with AI while preparing questions, they were able to generate next-generation questions, contribute to the learning process, revise incorrect questions, and successfully carry out the overall question preparation process. In addition, the innovative and up-to-date nature of AI technology supported the preservice science teachers' problem-solving and innovation skills. Especially during the implementation process, their continuous interaction with ChatGPT and engagement in group work were effective in developing their collaborative learning skills. In the related literature, it is emphasized that AI technology supports cognitive processes unique to human intelligence, such as reasoning, acquiring knowledge, problem-solving, thinking, and decision-making (Bayram & Çelik, 2023; Demir, 2004; Luger, 2009; Nilsson, 2010; Poole & Mackworth, 2017; Wagner, 2024). Group work fosters collaborative learning skills by encouraging equal participation and communication among students with diverse abilities and backgrounds (Slavin, 2022; Zorlu, 2020; Zorlu & Sezek, 2019, 2020). In addition, it is stated that AI provides various advantages to educators in educational settings, particularly in processes such as question generation, visual design, lesson planning, and instructional material development (Holmes et al., 2021). Furthermore, with the help of AI tools, it becomes possible to use time more effectively, increase efficiency, and create goal-oriented learning environments (Adams & Thompson, 2025; Jang & Choi, 2025; Salkovska et al., 2024; Wang, 2021).

In the post-tests of the TSIS and its subscales ("Social Information Processing", "Social Skills", and "Social Awareness"), it was found that the preservice science teachers' post-test scores were higher than their pre-test scores, and this difference was statistically significant. Based on these findings, it can be concluded that the AI-assisted question generation process contributed to the enhancement of the preservice science teachers' social intelligence. During this process, preservice science teachers researched information, shared it within their groups and in the classroom, interacted with ChatGPT, carefully listened to the knowledge and views of others in group work, and benefited from the feedback provided—all of which emerged as important factors supporting the enhancement of social intelligence. In the AI-assisted question generation process, students worked collaboratively in groups.

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Furthermore, their high levels of interest, attitudes, and motivation toward AI encouraged active participation in group work (Al-Badi et al., 2022; Huang & Qiao, 2024). In an AI-assisted process based on group work, participants are also given the opportunity to focus on intra-group interactions. This is considered to provide an appropriate foundation for the enhancement of social intelligence. Goleman (2007) has defined social intelligence as the ability to understand others' emotions and intentions, to enhance appropriate social responses, and to be effective in interpersonal relationships. The preservice science teachers' active involvement in group discussions, consideration of others' views, provision of constructive feedback, and demonstration of empathetic behaviors contributed to the enhancement of their social intelligence. AI-based applications help create learning environments that promote students' active participation and are conducive to active learning (Hardaker & Glenn, 2025; Jang & Choi, 2025; Qin & Zhang, 2025). In the context of social intelligence, the process whereby individuals understand others' emotions, intentions, and behaviors, and engage in effective interaction while developing appropriate social responses, comes to the forefront (Goleman, 2007; Platonova et al., 2021; Sailinova et al., 2024). When the preservice science teachers' views were examined in the IF, they expressed that the AI-assisted question preparation process created interaction-based learning environments, enabled collaborative correction of erroneous questions, and fostered learning through experience. These views support the idea that social intelligence develops through interaction and collaboration during the process. Today, one of the categories of AI software in education is intelligent support for collaborative learning (Luckin et al., 2016). For example, one participant (PST17) stated, "*To use artificial intelligence efficiently, assignments—just like question preparation—can be designed in collaboration with AI,*" highlighting that AI-assisted question generation offers not only individual but also collaborative learning opportunities. In addition, the observed improvement in the social awareness subdimension indicates that teacher candidates developed a more sensitive and empathetic approach while interacting both with AI and their peers. According to the participants, especially the feedback received during the process reinforced behaviors such as being open to different perspectives and valuing their peers' contributions. This finding suggests that AI-assisted learning environments may positively influence not only individual learning outcomes but also learners' social-emotional skills (Zawacki-Richter et al. 2019).

In the post-tests of the CTDS and its subscales ("Reflective Scepticism" and "Critical Openness"), it was found that the preservice science teachers' post-test scores were higher than their pre-test scores and that this difference was statistically significant. These findings indicate that the AI-assisted question generation process improved the preservice science teachers' critical thinking dispositions. This improvement can be attributed to factors such as exchanging ideas through group work, incorporating feedback into the process, revising questions based on different perspectives, questioning the quality of the prepared questions, and critically evaluating one's own experiences. Critical thinking disposition is defined as an individual's willingness and tendency to apply critical thinking (Facione, 2000). Paul and Elder (2019) have emphasized that the foundation of critical thinking lies in the individual's conscious questioning of their own thought processes and the ability to evaluate multiple perspectives. Within the scope of the study, reviewing the questions prepared by other groups using a structured evaluation rubric stands out as an effective practice that supported the enhancement of preservice science teachers' critical thinking dispositions. Moreover, the participants' abilities to formulate accurate prompts, learn by trial and error, perform self-assessment, revise incorrect questions, and identify the challenges encountered during interaction with ChatGPT demonstrate that their critical thinking processes were actively engaged. When the preservice science teachers' views are examined in the IF, these results are supported. One participant (PST12) stated, "*AI detects flawed questions, but it is up to us to understand and correct them*," clearly revealing how the process triggered critical thinking. These findings are consistent with previous studies showing that reflective and collaborative learning environments supported by technology are effective in developing critical thinking (Abrami et al., 2015). Factors such as learning through experience, personal development, evaluating feedback, and recognizing the limitations of artificial intelligence have strengthened preservice science teachers' critical thinking sub-dimensions, namely reflective scepticism and critical openness.

It was found that there were statistically significant and highly positive correlations between the post-test scores of TCSTS, TSIS, and CTDS, as well as their respective subdimensions. The presence of high-level positive relationships suggests that the implementation process in the study contributed to the enhancement of social intelligence, and also simultaneously enhanced domain-specific skills and critical thinking dispositions. In particular, during the AI-assisted question preparation process, individuals' effective use of technology, along with their collaboration efforts, enabled them to actively engage in their social intelligence. In addition, the encouraging nature of AI and the requirement for group work played an important role in the enhancement of social intelligence. At the same time, the participants' ability to critically evaluate the content they prepared contributed to the improvement of

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their critical thinking dispositions. This simultaneous enhancement emerges as a noteworthy finding, indicating that social intelligence, 21st-century skills, and critical thinking dispositions should be considered together in the learning process. The correlations between TSIS, CTDS, and TCSTS support the idea that social intelligence interacts dynamically with cognitive, critical, and digital skills. This finding is also consistent with the characteristics of social intelligence (Goleman, 2007; Platonova et al., 2021; Sailinova et al., 2024). AI-assisted group work may have allowed students to exchange ideas and thereby improve both their social and analytical skills. The relationships between the 21st Century Skills Teaching Scale (TCSTS), the Tromsø Social Intelligence Scale (TSIS), and the Critical Thinking Disposition Scale (CTDS) indicate that 21st-century skills develop in conjunction with social intelligence and critical thinking dispositions. In particular, the use of AI tools in collaborative learning environments may have simultaneously enhanced preservice teachers' ability to integrate new and up-to-date technologies and their capacity for social interaction (Hwang et al. 2020). The correlations between CTDS, TSIS, and TCSTS suggest that critical thinking disposition is connected to both social intelligence and 21st-century skills. Critical thinking requires the consideration of multiple perspectives, inquiry, and conscious thought processes (Facione, 2000; Paul & Elder, 2019). The enhancement observed in this study appears to stem from a combination of planning for conscious thinking through effective use of technology (21st-century skills), increasing social awareness through group work (social intelligence), and valuing different perspectives.

Conclusions and Implications

This study examined the role of artificial intelligence (AI)-assisted question generation on the enhancement of preservice science teachers' social intelligence, critical thinking disposition, and 21st-century teaching skills. The research findings indicate that this process can play a significant role in enhancing the preservice science teachers' 21st-century skills, social intelligence, and critical thinking dispositions. The findings demonstrate that the integration of AI tools, particularly through collaborative group work and interactive engagement with ChatGPT, significantly contributed to the development of these key competencies. The support provided by AI during the question generation process facilitated access to current information, allowed for real-time feedback, encouraged critical reflection, and enhanced collaboration and communication within groups. These conditions collectively created an enriched learning environment where cognitive, social, and technological competencies were simultaneously nurtured. Importantly, the observed strong and positive correlations among the post-test scores of TCSTS, TSIS, and CTDS suggest that these skill domains are interdependent and mutually reinforcing. This highlights the value of designing integrated learning experiences that consider the holistic development of future educators.

Integrating AI tools such as ChatGPT into training programs may enhance preservice science teachers' engagement, reflection, and active participation. Structured activities involving AI-assisted question generation can serve as a practical method to foster 21st-century skills, critical thinking, and social intelligence in preservice science teachers' education. It is anticipated that implementing applications in which artificial intelligence is used not only for question generation but also for the enhancement of various types of instructional materials will contribute significantly to the integration of AI into teaching practices. While this study provides a meaningful contribution to literature in terms of the cognitive and metacognitive roles and effects of AI-assisted processes, further research examining different variables in the future will offer valuable insights into the adaptation of artificial intelligence within learning environments. The AI-assisted question generation process offers significant pedagogical value by promoting the integration of cognitive, social, and digital competencies. As AI technologies become increasingly prevalent in education, harnessing their potential in a pedagogically sound manner will be essential for preparing educators who are equipped to thrive in complex, dynamic, and interconnected learning environments.

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